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Control of Air Emissions from Hazardous Waste Combustion Sources: Field Evaluations of Pilot-Scale Air Pollution Control Devices

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CONTROL OF AIR EMISSIONS FROM HAZARDOUS WASTE COMBUSTION SOURCES: FIELD EVALUATIONS OF PILOT-SCALE AIR POLLUTION CONTROL DEVICES

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FOREWORD

Today's rapidly developing and changing technologies and industrial products and practices frequently carry with them the increased generation of solid and hazardous wastes. These materials, if improperly dealt with, can threaten both public health and the environment. Abandoned wastes sites and accidental releases of toxic and hazardous substances to the environment also have important environmental and public health implications. The Hazardous Waste Engineering Research Laboratory assists in providing an authoritative and defensible engineering basis for assessing and solving these problems. Its products support the policies, programs and regulations of the Environmental Protection Agency, the permitting and other responsibilities of State and local governments, and the needs of both large and small businesses in handling their wastes responsibly and economically.

This document describes the evaluation of three pilot-scale devices for controlling particulate and HCl emissions from the exhaust gas of a commercial hazardous waste incinerator. A wet scrubber, a dry scrubber, and a high temperature baghouse were tested. The effectiveness of the devices and performance problems experienced are discussed. The intended audience for this document includes those involved in optimizing the control of air emissions from hazardous waste incineration.

For further information, please contact the Alternative Technologies Division of the Hazardous Waste Engineering Research Laboratory.

David G. Stephan, Director
Hazardous Waste Engineering Research Laboratory

ABSTRACT

Pilot scale air pollution control devices supplied by Hydro-Sonic Systems, ETS, Inc., and Vulcan Engineering Company were installed at the ENSCO, Inc. Incinerator in El Dorado, Arkansas in the spring of 1984. Each of these units treated an uncontrolled slipstream of the incinerator exhaust gas. Simultaneous measurement of the total particulate and HCl in the gas streams were made at the inlet to and exit from the units using an EPA Method 5 sampling train. Particle sizing at both locations using Andersen impactors was also done. The units supplied by Hydro-Sonics Systems and ETS, Inc. exhibited a high degree of HCl and particulate matter control. The Hydro-Sonic Tandem Nozzle SuperSub Model 100 gave the best overall performance for HCl and particulate control and ability to accommodate the variable composition of the exhaust gas.

CONTENTS

Page

Foreword. iii
Abstract iv
List of Figures vii
List of Tables. viii
Acknowledgments ix

1. Introduction 1

    Background 1
    Approach 1

2. Test Source Description. 4

    Plant Description. 4
    Description of APCD Connection to Plant. 6

3. Test Method Description. 8

4. Hydro-sonics Air Pollution Control Device. 10

    General Description. 10
    Versions Tested. 12
    Test Results 14
    Conclusions. 25

5. ETS, Inc. Dry Scrubber 26

    General Description. 26
    Unit Tested. 28
    Test Results 28
    Difficulties Encountered 37
    Conclusions. 37

6. Vulcan Engineering Company Hi-Tac Filter 41

    General Description. 41
    Unit Tested. 42
    Test Results 42
    Hi-Tac Operating Conditions. 42
    Conclusions. 56

CONTENTS (Continued)

Page

7. Ceilcote IWS® System 57

General Description. 57
Test Results 60

8. Quality Assurance. 61

9. Conclusions 63

References 64

Appendix: Vendor Site Test Reports 65

LIST OF FIGURES

Figure Page

1 Schematic of incinerator system 5
2 General relationship of sampling ports and major components of the HydroSonics system 7
3 Steam hydro test configuration 11
4 Tandem Nozzle & Supersub test configuration 13
5 Cumulative particle concentration vs. particle diameter: HydroSonics APCD 22
6 Percent particles passing through APCD vs. particle diameter . 23
7 ETS dry SO_2 reactor 27
8 General relationship of sampling ports and major components of the ETS system 29
9 HCl removal efficiency: ETS unit 35
10a Cumulative particle mass versus particle diameter 36
10b Differential particle mass vs. particle diameter 38
11 Size-based particle removal efficiency: ETS unit 39
12 Schematic of Vulcan Hi-Tac mobile unit 43
13 General relationship of sampling ports and major components of the Vulcan system 44
14 Relationship of total mass removal efficiency and system flow rate: Vulcan unit 51
15 Relationship of total mass removal efficicney and air-to-cloth ratio: Vulcan unit 52
16 Cumulative mass concentration vs. particle size: Vulcan unit . 53
17 Differential mass concentration vs. particle size: Vulcan unit 54
18 Efficiency of particulate matter removal vs. particle size: Vulcan unit 55
19 Ceilcote ionizing wet scrubber. 58
20 Ceilcote system 59

LIST OF TABLES

Table		Page
1	Scrubber Inlet Summary of Test Results	16
2	Scrubber Outlet Summary of Test Results	18
3	Particulate and Chloride Removal Efficiencies: Hydro-Sonic Scrubber	20
4	Comparison of Fine Particle (<1 Micron) Enrichment Factors (Out/In) for Various Operating Conditions	24
5	Chemical Composition of Material Used in ETS Tests	30
6	Inlet Site Comparison Data	30
7	Summary Results: ETS Unit	32
8	Baghouse Inlet Summary of Test Results	33
9	Baghouse Outlet Summary of Test Results	34
10	Comparison of Fine Particle (<1 Micron) Enrichment Factors Out/In for ETS Impactor Runs	40
11	Inlet Site General Data	45
12	Hi-Tac Unit Operating Conditions	47
13	Vulcan High Temperature Baghouse Efficiency Summary	48
14	Scrubber Inlet Summary of Test Results	49
15	Scrubber Outlet Summary of Test Results	50

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RTI and ES wish to acknowledge the technical contribution of ENSCO, Inc.; Hydro-Sonic® Systems; ETS, Inc.; Vulcan Engineering; and Ceilcote Company and to express appreciation for their participation in this project.

SECTION 1

INTRODUCTION

BACKGROUND

Much hazardous waste generated has characteristics that make incineration the disposal method of choice. Incineration of these wastes must be performed according to the applicable regulations of the Resource Conservation and Recovery Act (RCRA) and State and local regulations. The RCRA regulations specify the destruction and removal efficiency (DRE) that must be achieved for principal waste components and set limits for the emission rates of particulate matter and hydrogen chloride (HCl).

Typical control devices that have been used to meet these limits are wet scrubbers of various designs, electrostatic precipitators, and fabric filtration systems (baghouses). These devices are of varying effectiveness in controlling fine particulate and HCl emissions sufficiently to be in compliance with the regulations. Many incineration facilities are having difficulty meeting the particulate standards due to high percentage of fine particulates formed in the process.

The purpose of this project is to evaluate innovative air pollution control devices and to test their performance on commercial-scale facilities. The specific goals are to examine the cleaning capabilities of each device under specified operating conditions. The pollutants to be monitored are (a) particulates; total mass, and as a function of particle size, and (b) hydrogen chloride (HCl).

The data developed in the project will be useful to EPA and others in the waste management community to assist in optimizing the control of air emissions from hazardous waste combustion.

APPROACH

In Phase I of the project, the current state of development of air pollution control devices (APCDs) that have the potential to control emissions from hazardous waste combustion devices was assessed and a number were recommended for field testing. Considering the funding reality for field testing, it was decided that no more than four units would be tested. It was also decided that each of the four should represent a different approach to control. The APCD vendors were contacted, the project goals described, and invitations to participate were made.

Four vendors with pilot units meeting the criteria agreed to participate. They are Hydro-Sonics® System, Inc.; Vulcan Engineering; and Ceilcote, Inc. The Hydro-Sonic® pilot unit is a wet scrubber that operates by fine atomization of water into the gas stream resulting in HCl capture and particle growth with final removal by cyclonic action. The ETS, Inc. unit uses dry lime injection for particulate capture. The unit provided by Vulcan Engineering is a high temperature (>550°C, 1000°F) metallic weave filtration system. It is not currently designed for acid gas control. The Ceilcote unit applies an electric charge to the incoming particulate which then adheres to the packing material and is removed by water spray.

Several commercial hazardous waste incineration facilities were contacted to select the host facility for the tests. Criteria used for selection were: regulatory authorities would allow the tests, appropriate types of waste (significant ash and chlorine) being incinerated regularly; facility design would allow safe removal of slipstream of combustion products upstream of emission control equipment; and corporate management was willing to allow the testing. Of those companies willing to participate, ENSCO, Inc.'s incinerator in El Dorado, Arkansas best met the above criteria.

The ENSCO, Inc. facility primarily incinerates PCB-contaminated capacitors and oils. The capacitors are shredded and fed into a rotary kiln. Contaminated oils are incinerated in an afterburner following the rotary kiln. The waste mix insured that a significant amount of particulate matter and HCl would be in the combusted gas stream leaving the process.

Between the last, nonfired, afterburner and the emission control equipment is an emergency bypass stack. This location is ideal for removing a slipstream gas from the system. Removing only a slipstream from the process has several advantages. It allows the plant to operate normally without fear of upset due to pilot unit malfunction. It allows conditioning of the gas, primarily temperature control, to accommodate design limitation of pilot units. The use of a slipstream allows operation of the pilot unit over a wide range without requiring a change in plant operation or possible out-of-compliance conditions.

A major advantage was afforded due to the location and design of the bypass system. By withdrawing the slipstream from a location well up on the stack, most of the large particulate matter remains with the main gas flow. Thus, the slipstream contains primarily the fine particulate matter. (The concentrations of gaseous components, like HCl, are not affected by this biasing of the gas particulate composition.) Since the samples taken at the inlet to the pilot unit will not be dominated by the larger particulate, which most units can easily control, an assessment of the unit's capability for fine particulate control is much easier and more accurate.

The necessary duct work and support facilities were constructed at the ENSCO plant in January and February 1984. Testing of the Hydro-Sonic® unit was accomplished during the week of March 12 and 19. The ETS, Inc. unit was tested in two phases, due to maintenance on the incinerator, beginning April 2 and ending April 27. In the period May 14 to May 24, the Vulcan Hi-Tac baghouse was tested.

After a pilot unit was connected to the installed duct work, a slip stream of particulate-laden gas from the emergency bypass stack was drawn through the unit. Inlet and outlet gas streams were sampled simultaneously by EPA Method 5 for the concentration and total mass of the particulate matter and HCl. Particle size distributions were also determined at both locations.

Each APCD vendor operated his own equipment and was allowed to vary conditions to test the performance of the unit. ENSCO operated their facility in a routine manner during these tests. No special fuel blends on operating procedures were used to accommodate the units.

A 2-week period was allotted for testing each unit. The testing program was designed to obtain three sets of Method 5 tests and one set of impactor data daily. Laboratory space was provided to set up the analytical equipment needed to complete most of the required analyses onsite. Most Method 5 particulate and HCl data were available within 24 to 48 hours after the test.

Quality assurance and quality control procedures were designed into the field sampling and analysis program. The RTI field test supervisor, Eugene Tatsch, has extensive experience in field and laboratory audits. All Method 5 and impactor tests were evaluated by Mr. Tatsch. Audit samples for HCl were evaluated onsite using the identical procedures as for sample recovery.

SECTION 2

TEST SOURCE DESCRIPTION

The host plant for these tests was ENSCO, Inc.'s incineration complex in El Dorado, Arkansas. This permitted facility primarily incinerates polychlorinated biphenyl (PCB) contaminated oils and capacitors.

PLANT DESCRIPTION

The plant is designed to receive and incinerate whole capacitors (see Figure 1). The capacitors are fed into two parallel shredders. The shredded parts, which may be up to 8 or 9 inches in size, are transported with a 20-inch diameter auger into a rotary kiln. The refractory-lined kiln is 7 feet internal diameter and 36 feet long. Feedrate to the kiln is controlled to maintain a temperature of about 2400°F. Very large solids which exit the kiln are removed with a conveyor. The kiln exit gas passes through a cyclone which removes much of the large suspended particulate matter. The gases then pass into a two-chambered afterburner referred to as the thermal oxidation unit (TOU). The upstream side of the afterburner can be fired with PCB-containing oils or other high Btu liquids. Natural gas can also be introduced into this unit to maintain the high temperatures required for complete destruction of the waste. The downstream side of the afterburner is not fired. It supplies additional residence time for the thermal oxidation reactions to occur. Large particulate carried over from the kiln and/or introduced with the liquid fuels settle out in these chambers. The particulate gradually builds up, partially blocking the exhaust ductwork, and requires additional vacuum at the scrubber to maintain adequate draft at the kiln. A plant shutdown is required to remove these ashes when the draft requirements exceed that available.

Gases leaving the TOU are drawn into the custom-designed wet scrubber. This unit consists of two circulating water loops. The first, prequench, loop removes the bulk of the particulate and HCl. Lime slurry is added for pH control. Blowdown is routed to a pond for solids settling. The clarified water is recycled. The second loop is comprised of a jet eductor, knockout vessel, and demister. Fresh makeup water is added to maintain inventory. All blowdown from this loop is used as a makeup to the first loop. No water is discharged from this system except for that evaporated and carried out with the stack gas.

The incinerator typically operates 24 hours per day, 7 days per week. In general, wastes of a specific class are accumulated onsite until sufficient quantity is available for burns of at least one day. This permits achieving and maintaining steady-state incineration conditions. During these tests, wastes accumulated were incinerated on the schedule determined by plant management. No special wastes were burned or excluded. Close contact was

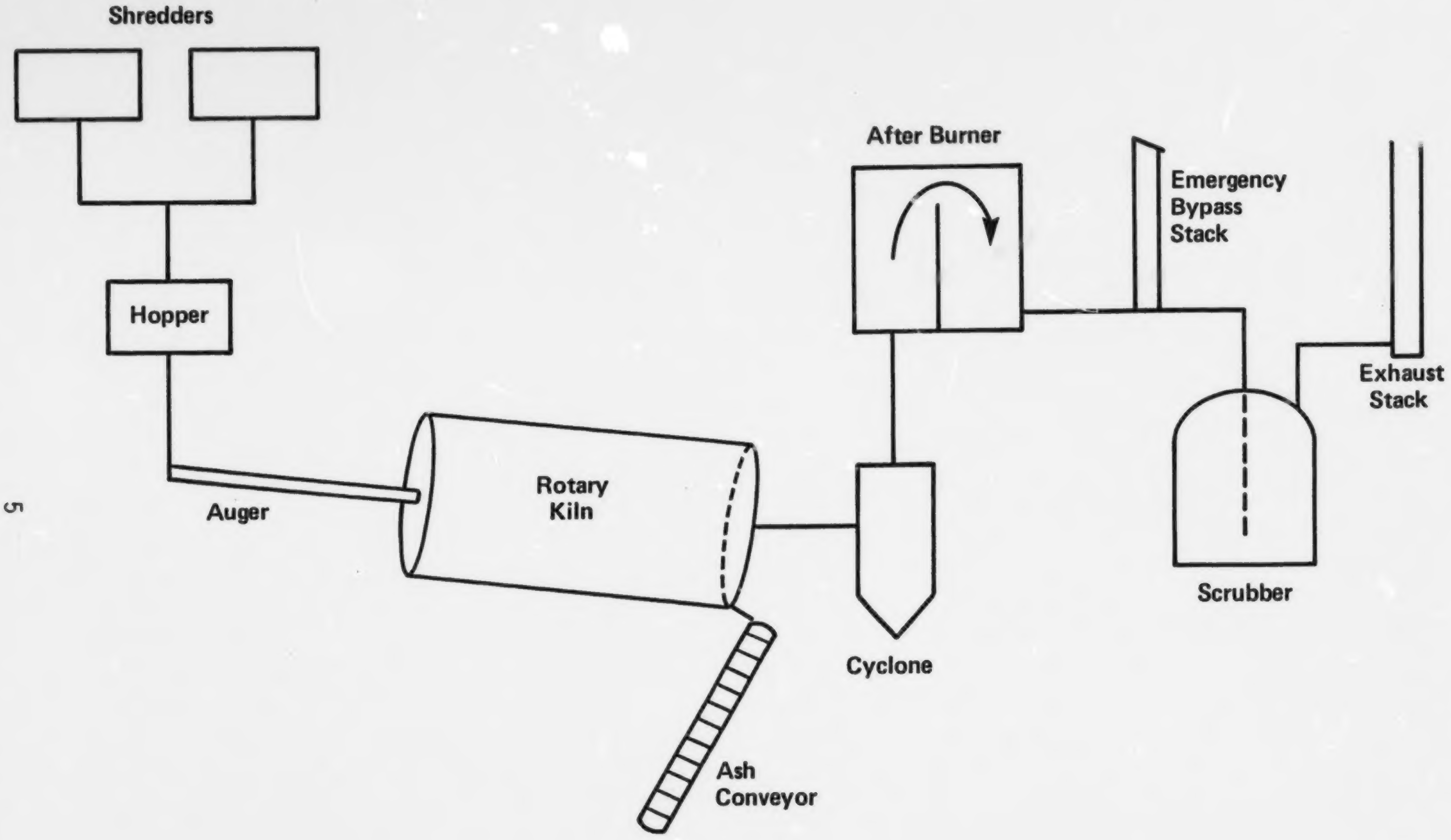

Shredders
Hopper
Auger
Rotary Kiln
Ash Conveyor
Cyclone
After Burner
Emergency Bypass Stack
Scrubber
Exhaust Stack

Figure 1. Schematic of incinerator system.

maintained with plant personnel so that the APCD testing spanned only one operating condition, insofar as possible.

DESCRIPTION OF APCD CONNECTION TO PLANT

Shown schematically in Figure 2 are the connections made to the incinerator facility to conduct gas to the APCDs. Connection was made to the emergency bypass stack. The stack, located between the TOU and the scrubber, is refractory lined. Openings around the stack cap were plugged to prevent air infiltration into the stack. (Vacuum in the stack varied between 1 and 6 inches of water.) The material used would not hamper opening the stack in an emergency. A 30 cm (12-inch) stainless steel duct is connected to a flanged opening in the stack. The duct runs horizontally from the stack toward the APCD about 15 feet. The duct then connects to a vertical section leading to a 60 cm (2 feet) diameter 10 feet long Hastalloy cooling section. Gas cooling is by direct water spray. A temperature control device mounted at the exit of the cooling section modulates the water flow. The cooled gas was then ducted to the APCD connection via a 30 cm (12 inch) ID 17 foot horizontal run of insulated carbon steel pipe. The APCD gas inlet sample ports are located near the midpoint of this duct. The two (3.5 inch) ports were on the vertical and horizontal axes perpendicular to the gas flow.

Referring to Figure 1, it is apparent that the plant exhaust gases do not normally flow through the bypass stack. These gases are drawn from the main exhaust duct into and through the bypass stack by the suction equipment supplied with the APCDs. Clearly, the placement of the slipstream duct results in withdrawing a gas containing a lower concentration of the larger particulate matter than exists in the main duct. This placement does not affect the relative concentrations of gaseous components. Since control of large particles is normally easily accomplished by any well-designed and operated APCD, the selection of this gas offtake location allows us to concentrate on removal of the fine particulates. If this type biasing had not been done, determining the APCD control capability for fine particulates would have been complicated.

Gas flows through the slipstream duct were varied by the APCD operators to meet the needs of their unit. In general, the flow rates were between 1,000 and 4,000 ACFM. The fans on the APCD were normally able to pull the needed gas flow against the vacuum in the bypass stack. However, when ash built up on the TOU, the APCDs experienced considerable difficulty withdrawing gas against the stack vacuum of up to 6 inches of water.

Some initial difficulty was experienced attaining gas temperatures above 300°F at the inlet ports. After repair of the leaking steam valve at the bypass stack, the gas cooling section performed quite well and kept temperatures in the 400°-600°F range.

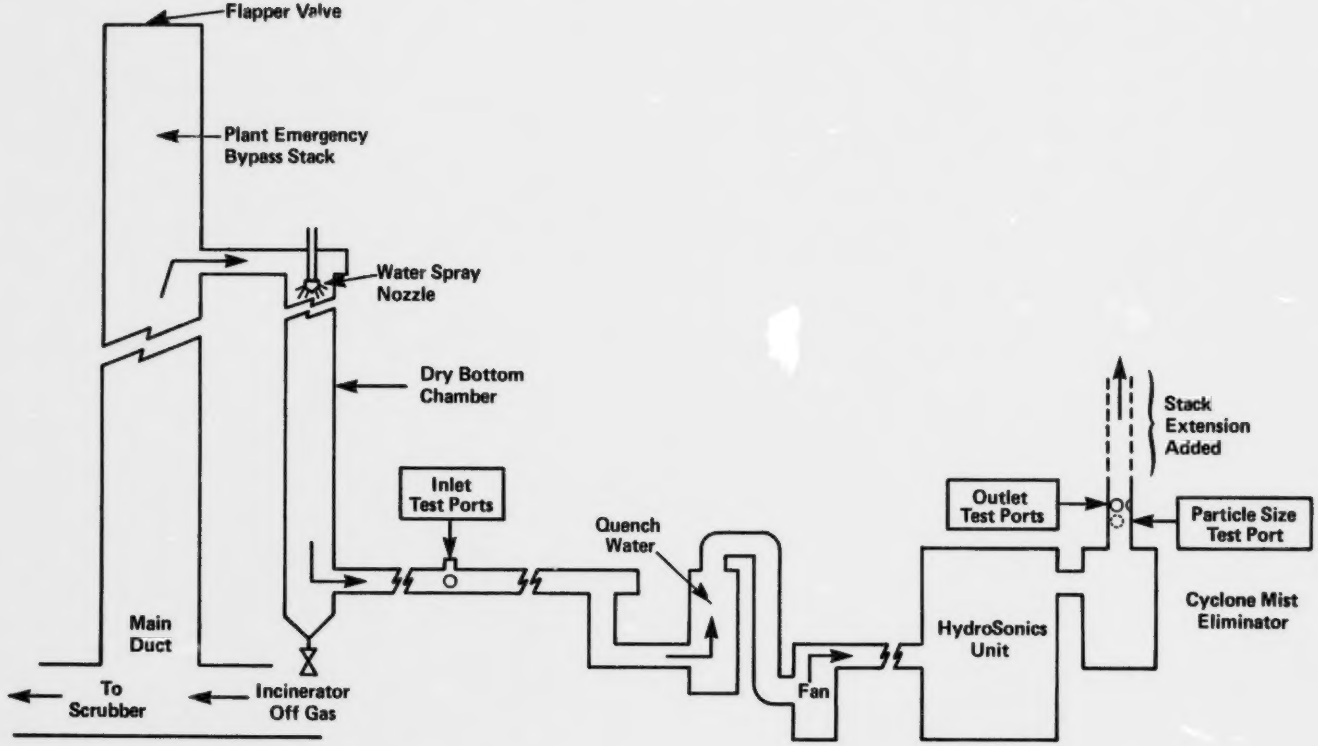

Flapper Valve
Plant Emergency Bypass Stack
Water Spray Nozzle
Dry Bottom Chamber
Inlet Test Ports
Quench Water
Main Duct
To Scrubber
Incinerator Off Gas
Fan
HydroSonics Unit
Outlet Test Ports
Stack Extension Added
Particle Size Test Port
Cyclone Mist Eliminator

Figure 2. General relationship of sampling ports and major components of the HydroSonics system.

SECTION 3

TEST METHOD DESCRIPTION

All emission measurements field work was performed by Engineering Science, Inc., Fairfax, VA, under subcontract to RTI. An RTI project coordinator was onsite to direct the test.

The test program was designed to withdraw a slipstream of incinerator exhaust gas and to test the APCDs performance in removing particulate and HCl. It was necessary, therefore, to measure these pollutants at the inlet to and exit from the air pollution control device (APCD). Sufficient equipment and personnel were available to conduct testing simultaneously at these two locations.

Both the concentration of total particulate in the gas stream and particulate mass per unit time were determined using EPA Method 5. The impinger solutions in the back half of the train were analyzed to obtain equivalent information for HCl. EPA Method 5 is the approved method for determining particulate emissions from stationary sources. A heated, glass-lined, probe equipped with a stainless steel button-hook nozzle was inserted into the gas stream. The particulate laden gas is drawn into the probe isokinetically (gas velocity in button-hook nozzle is the same as gas velocity at sampling point). The particulate matter is collected on a heated preweighed glass filter. The filtered gas then passes through two impingers which contain water, one empty impinger, and one silica gel impinger before entering the pumps and control module. Gas samples are withdrawn at specified locations within the duct to compensate for possible stratification. The particulate catch is collected from all surfaces from the filter forward (front half). The increase in water volumes and silica gel weight in the back-half is a measure of the moisture content of the gas.

The particle size distribution at both the inlet and outlet test locations was determined using Anderson cascade impactors. Cascade impactors classify particles on the basis of their aerodynamic properties. Impactors are constructed with multiple stages and with one or more jets (holes) per stage so that the total stage jet area decreases as the sampled gas progresses through the device. As a result, gas and particulate velocities increase proportionally, and successively smaller diameter particles impact on the weighable substates. A backup filter captures any remaining entrained particles. Other measured values, such as gas flow rate and temperature, are then used to calculate the size of the particles that have impacted on each stage. Particle weights are then used with the calculated particle diameters to determine the size-mass distribution. This distribution is obtained independently of particle shape or density.

Due to the large difference in particle loadings between the inlet and outlet sites, it was not possible to obtain simultaneous impactor runs spanning the same time interval. Typically 5 to 7 minutes operation at the inlet site product optimum stage loadings. Operation for 60 to 90 minutes was required at the outlet location for collection of adequate sample. Impactor runs were arranged to coincide with one or more Method 5 runs.

An onsite laboratory was set up to reduce as much of the test data as possible. Facilities were available to properly clean all of the test equipment, recover samples, and to desiccate the particulate catches. A certified accurate balance was used to weigh all of the samples. A chloride ion-specific electrode and supporting electronics were available to measure chloride concentrations in the Method 5 train back-half impingers. The necessary volumetric glassware and certified analysis chloride reagent were available to prepare calibration standards and to measure the volume of impinger solutions. Chloride audit solutions were also onsite to audit this procedure.

All data, except the chloride analyses, were recorded on pre-prepared data forms. The chloride data were recorded in a laboratory notebook.

The impactor data were processed at the conclusion of the test using the Particulate Data Reduction (PADRE) data program [1]. PADRE is installed at the EPA National Computer Center in Research Triangle Park, NC, and is maintained by EPA. It is available to EPA personnel, authorized contractor, the States, and the private sector. The interactive, "user-friendly" program prompts the user for all test data required to perform the calculations. In addition, it checks for "fatal" errors (e.g., substrate weight loss) and will not proceed until the error is corrected. "Non-fatal" errors such as excessive jet velocities are detected and appropriate warnings issued.

After data entry, calculation proceeds in two major phases: calculating the basic diameter-concentration value pairs, and curve fitting using these points. Particle diameters are calculated for impactor stages and inferred for the backup filter; they are user-supplied for precutters. The D_{50} model, which assumes 50 percent collection efficiency for a stage under operating conditions is used. Once the D_{50} and mass concentration have been calculated for each stage, the size-mass distribution may be plotted. A parabolic interpolation is used to estimate the cumulative and differential concentrations at standard diameters of 20, 15, 10, 6, 2.5, 1.25, 1.0, 0.625, and 0.3 microns.

SECTION 4

HYDRO-SONICS AIR POLLUTION CONTROL DEVICE

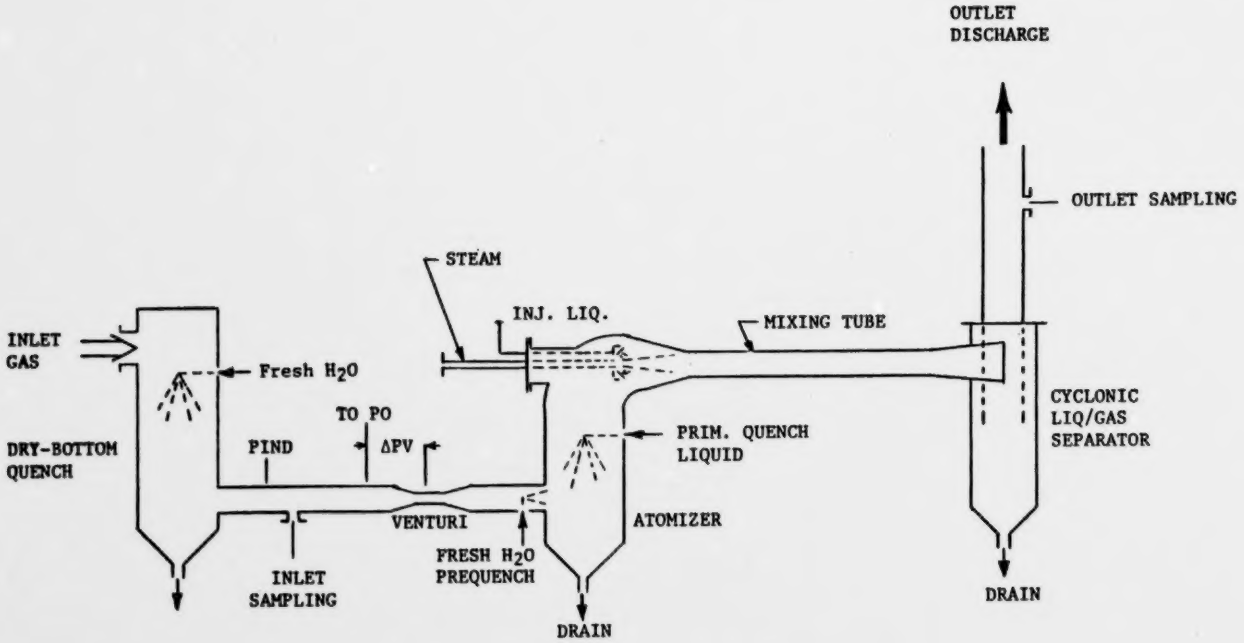
GENERAL DESCRIPTION

Lone Star Steel Co. originally developed this wet scrubber to control particulate emissions from various iron and steelmaking operations. It has been used on such sources as electric arc furnaces, coke oven emissions, open hearth steel furnaces, and sintering plants. The scrubbers have also been used on exhaust streams containing uranium hexafluoride and its hydrolysis products with particulate removal efficiency consistently exceeding 99 percent. Efficiencies of 99.997 percent HCl removal were reported by a customer using the scrubber on a vent stream containing trichlorosilane. Commercial applications have included a radioactive waste incinerator, a PCB incinerator, and a municipal waste incinerator.

There are three versions of the scrubber which are described below. All versions have the same basic concept. Water is atomized into the waste gas stream forming water droplets of about the same size as the particulate. The gas stream then enters a turbulent contact zone in which the particles are wetted and vapors are absorbed. Particle growth then takes place in an agglomeration zone. Because of the design, a single waste droplet may contain hundreds of micronic and submicronic dust particles. As a result of the growth of droplets containing particulate into increasingly larger size, the initial size of the particulate has only a small effect on its removal. Actual removal of the agglomerated particle is accomplished in a specially designed low-pressure-drop cyclone. Water and particulate are gravity drained from the cyclone bottom, and the cleaned gases exit through the top. Demisters are not required.

There are three versions of the systems: the Steam-Hydro, the Tandem Nozzle, and the SuperSub. All versions described below use the cylonic system described above for final particle-gas separation.

The Steam-Hydro, depicted in Figure 3, employs a supersonic ejector drive to provide the energy for pumping and cleaning the polluted gas. Steam or compressed air is commonly employed as the working fluid. The gas is drawn into the unit by the ejector nozzle which is fitted with a water injection ring at the exit of the nozzle. The expanding jet causes violent shattering of the water droplets and turbulent mixing of gas and water. This unit is used for gas streams containing mostly fine particulates. If steam is used as the working fluid, power consumption can be as much as 10 times greater than that required for an air ejector venturi. The steam version is most attractive when there is a source of waste heat available to generate the high-pressure steam.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CYCLONIC
LIQ/GAS
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VENTURI
ATOMIZER
INLET
SAMPLING
FRESH H_2O
PREQUENCH
DRAIN
DRAIN

Figure 3. Steam hydro test configuration.

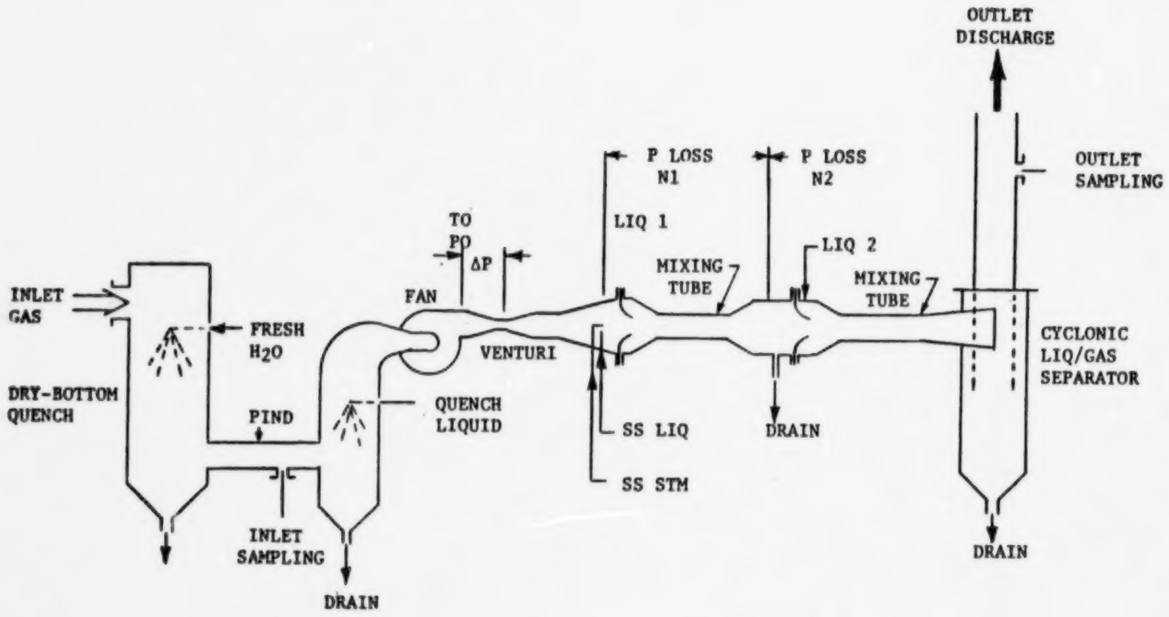
The Tandem nozzle scrubber uses a fan drive to pump the polluted gas and to provide the energy to generate the fine water droplets. The system depicted in Figure 4 used two subsonic nozzles and agglomeration sections in series. Both nozzles are equipped with water spray rings. The first section serves to condense vapors, remove the larger particulates, and initiate growth of the fine particulate. Additional water is atomized at the exit of the second nozzle and is turbulently mixed to continue the agglomeration of the particles. This unit is typically used in applications in which large gas volumes make the use of steam or air costs prohibitive. Also, because the atomization energy is lower, application is generally on streams with lower percentages of very fine particulate. This unit uses more water than the Steam-Hydro, but the water requirement is about comparable to a venturi scrubber.

The SuperSub version of the system is a combination of the above two system concepts. The system is depicted in Figure 4. A small supersonic ejector (steam or air) is located upstream of the subsonic nozzle. The systems main driving force is fan power as in the Tandem Nozzle version. This arrangement provides good water atomization for fine particle control coupled with the lower energy requirements of the fan drive. Water consumption is about the same as a venturi scrubber. It would be expected, because of the design, that the SuperSub performance would be intermediate to the Steam-Hydro and the Tandem Nozzle. However, the manufacturers recommend testing all combinations since particulate characteristics may affect actual results obtained.

VERSIONS TESTED

The Model 100 Steam-Hydro, Model 100 Tandem Nozzle Hydro, and Model 100 SuperSub Tandem Nozzle Hydro versions of the scrubber were tested during this program. The pilot unit is designed so that the hardware peculiar to each version is interchangeable. Thus, two men can convert the unit from a Steam-Hydro to a SuperSub in about four (4) hours.

The incinerator slipstream duct was connected to the 30 cm (12") diameter inlet duct to the unit fan. An emergency water spray was installed in this duct to protect the unit from excessive temperatures (none were experienced during the testing). A centrifugal fan was not operated during the Steam-Hydro tests. It provided the gas motive force for the Tandem Nozzle and SuperSub versions. After leaving the fan, the gas passed through a 6.138-inch throat venturi. Gas flow rate into the system is normally measured here. During these tests, the information collected was used only to compare with the flow rate measured by the test crew at the inlet locations in the slipstream duct. The gas passed through an 8-inch duct into the main scrubbing chambers previously described. The scrubber chambers are constructed of fiberglass and can be easily lifted and bolted in place by two men. The chambers varied from about 30 cm (12 inches) in diameter on the inlet to about 13 cm (5 in) at the outlet end. Overall length was either 1 meter (3 ft) for the Steam-Hydro or 2 meters (6 ft) for the Tandem Nozzle and SuperSub. Outlet gases from the scrubbing chambers tangentially entered the vertical cyclonic separator which was about 45 cm (18 in) in diameter by 2.5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LIQ 1
LIQ 2
MIXING
TUBE
MIXING
TUBE
INLET
GAS
FAN
FRESH
H2O
VENTURI
CYCLONIC
LIQ/GAS
SEPARATOR
DRY-BOTTOM
QUENCH
PIND
QUENCH
LIQUID
SS LIQ
DRAIN
SS STM
INLET
SAMPLING
DRAIN
DRAIN

Figure 4. Tandem Nozzle & SuperSub test configuration.

meters (8 ft) tall. A 30-cm (12-in) outlet stack exited vertically from the cyclone.

The entire unit (except for the fan and venturi section) is mounted on a portable 2 m x 4 m (6 ft x 12 ft) skid. Overall height of the unit excluding the cyclone exit stack is about 2.5 m (8 ft). A control panel is mounted on the skid. The various values, flow meters, and magnehelix needed to control steam flow, water flow, and monitor pressure drops were mounted on the panel.

The rated capacity of the unit is 1,000 ACFM. During the test period, gas flow rate was typically 750 ACFM.

No major operation problems were encountered during the test. There are only two operational problems worthy of note. The fan failed near the end of the test due to a bearing failure. Plugging of the water spray nozzles was experienced when the ENSCO scrubber water was used. The water apparently contained too much large size particulate matter to pass through the small holes in the atomizer ring. With clean water as clarified scrubber water, no problems were encountered. The operators were consistently able to bring the unit up from a cold condition and be ready for testing within 1 hour.

TEST RESULTS

Test data for these units were collected between March 15, 1984, and March 23, 1984. The following parameters were applicable to the cleaners tested (data supplied by Hydro-Sonics systems).

1.	Steam-Hydro	
	Steam used, pounds per pound of inlet gas	0.144 to 0.191
	Steam pressure in psig	92 to 98
	Injection water at steam nozzle exit pounds per pound of inlet gas	0.877 to 1.073
	Cooling water, pounds per pound of inlet gas	0.578 to 0.855
	Prequench water, pounds per pound of inlet gas	0.203 to 0.244
2.	Tandem Nozzle	
	Pressure across cleaning unit in inches of water gauge	32.5 to 35.0
	Injection water for cooling gas, pounds per pound of inlet gas	0.813 to 1.829
	Injection water at the first nozzle exit, pounds per pound of inlet gas	1.007 to 1.426
	Injection water at the second nozzle exit, pounds per pound of inlet gas	0.733 to 1.298
3.	Tandem Nozzle SuperSub	
	Steam used in steam nozzle, pounds per pound of inlet gas	0.039 to 0.041
	Injection water at steam nozzle exit, pounds per pound of inlet gas	0.173 to 0.218
	Steam pressure in psig	110

Pressure across cleaning unit in inches of water gauge	31.2 to 34.4
Injection water for cooling pounds per pound of inlet gas	0.562 to 0.826
Injection water at the first nozzle exit, pounds per pound of inlet gas	0.891 to 1.364
Injection water at the second nozzle exit, pounds per pound of inlet gas	1.229 to 1.293

Given in Table 1 are the reduced data for total particulate and chloride for each APCD inlet sample taken. Equivalent data for the APCD outlet are given in Table 2.

In Table 3 these data are organized by the APCD operating version. With the exception of two tandem nozzle runs (10 and 11), chloride removal for all combinations was greater than 98 percent. Runs made using recycle water from the ENSCO scrubber show higher removal of chloride than those using freshwater. Since the recycle water contained some alkalinity, this is not surprising. In a commercial application, alkalinity would be added to the scrubbing water. Thus, chloride removals of 99 percent or better should be expected for any version of this unit.

Particulate removal efficiency ranges from about 82 to 88 percent for the Steam-Hydro and Tandem Nozzle versions. The SuperSub version achieved a particulate removal efficiency of about 95 percent. It should be noted that these removal efficiencies refer only to the gas stream brought into the APCD and not the efficiency that might be obtained on the entire gas stream from the ENSCO incinerator. Since the APCD connection to the main gas duct should have resulted in a bias toward the smaller particles, we would expect that substantially higher removal efficiencies would have been obtained if the APCD had been treating the unbiased gas stream.

The plot of the cumulative mass as a function of particle size (Figure 5) shows that the large fraction of the particulate matter exists below 1 micron, whether at the inlet or outlet of the control device. The percent of particles passing through the unit, as a function of particle size (Figure 6), shows wide variability, partially due to the different operating conditions shown, and partially due to the need for more impactor data. Also, it must be noted that design philosophy of the unit is to agglomerate fine particles. Thus, it is to be expected that some the submicron particles entering the device exit as particles greater than 1 micron in size. These data indicate that the SuperSub configuration is the most effective of the versions tested for control of the submicron particulate matter from this source.

Both the Steam Hydro (SH) and the Tandem Nozzle (TN) configurations are designed to control particles with diameters above 2 to 3 microns. The SuperSub (SS) configuration is designed to grow the smaller particles to above this diameter for subsequent capture by the standard system mechanism. This is realized clearly in Table 4. While the incoming gas stream is rich in fine particles, only the SuperSub configuration shows a significant relative reduction in particles on the impactor filters (i.e., less than 1.0 microns).

TABLE 1. SCRUBBER INLET SUMMARY OF TEST RESULTS

Run Code	Moisture (%)	Orsat Analysis (%)		Exhaust Flow Rate (SCFM)	Stack Temp. F.	Isokinetic (%)	Concentration (gr/scf)		Emission Rate (lb/hr)	
		CO_2	O_2				Particulate	Chloride	Particulate	Chloride
1	28.29	7.2	11.2	754.9	617	102.8	0.286	2.57	1.8511	16.6297
2	27.25	8.4	9.8	803.5	653	100.0	0.668	3.19	4.5976	21.9796
3	31.38	7.3	11.0	707.4	645	111.2	0.324	3.83	1.9614	23.2241
4[a]	23.16	7.2	11.8	716.2	633	95.4	0.636	3.69	3.9054	22.6477
5	33.76	8.3	10.1	724.7	691	108.1	0.504	4.97	3.1328	30.8377
6	27.34	7.6	11.4	689.6	674	98.9	0.705	5.22	4.1675	30.8477
7	28.99	8.6	10.9	654.9	719	103.7	0.273	3.87	1.5318	21.7272
8	26.55	6.5	12.4	691.6	601	95.3	0.308	3.41	2.2528	20.2020
9	27.54	7.0	12.0	648.8	599	97.9	0.353	3.62	2.0205	20.1335
10	32.77	5.0[b]	14.0	678.6	548	105.3	0.630	5.05	3.6641	29.3662
11	30.93	6.9	11.6	680.8	539	92.3	0.595	3.87	3.4732	22.6061
12	30.86	7.4	10.7	691.8	536	98.3	0.331	3.25	1.9619	19.2815
13	32.46	7.2	11.2	684.7	516	98.8	0.350	3.05	2.0563	17.8822

[a] Unacceptable post test leak check.

[b] Orsat Analyses are suspected to be incorrect, probably due to a leakage in the system during that test.

TABLE 1.(continued).

Run Code	Moisture (%)	Orsat Analysis (%)		Exhaust Flow Rate (SCFM)	Stack Temp. F.	Isokinetic (%)	Concentration (gr/scf)		Emission Rate (lb/hr)	
		CO_2	O_2				Particulate	Chloride	Particulate	Chloride
14	26.51	7.2	11.2	692.9	647	100.8	0.690	4.62	4.0965	27.4534
15	21.54	7.5	9.1	764.1	643.	93.6	0.637	2.83	4.1731	18.5521
16	22.42	7.0	11.4	745.1	661	95.5	0.669	6.19	4.2740	39.5060
17	26.50	7.0	12.1	761.2	537	94.9	0.591	4.27	3.8572	27.8314
18	26.90	8.0	10.1	789.7	592	85.1	0.389	4.54	2.6315	30.7037

TABLE 2. SCRUBBER OUTLET SUMMARY OF TEST RESULTS

Run Code	Moisture (%)	Orsat Analysis (%)		Exhaust Flow Rate (SCFM)	Stack Temp. F.	Isokinetic (%)	Concentration (gr/scf)		Emission Rate (lb/hr)	
		CO_2	O_2				Particulate	Chloride	Particulate	Chloride
1	46.49	7.0	11.1	1106.8	181	127.9	0.026	0.035	0.244	0.329
2	48.17	6.9	12.1	1122.8	181	130.4	0.045	0.021	0.438	0.206
3	51.06	6.3	11.5	1015.0	184	123.4	0.029	0.022	0.249	0.195
4	45.44	6.6	12.6	1052.3	180	107.3	0.107	0.033	0.978	0.294
5	38.46	6.3	12.7	1041.7	166	106.2	0.033	0.077	0.294	0.684
6	33.76	6.7	12.4	1072.7	164	110.7	0.029	0.031	0.269	0.281
7	36.08	6.8	11.6	1068.6	164	112.1	0.028	0.034	0.257	0.310
8	42.67	5.5	13.8	1114.3	174	124.1	0.044	0.012	0.363	0.117
9	43.86	6.6	12.1	1119.6	173	120.6	0.039	0.012	0.363	0.112
10	15.74	6.1	12.8	953.6	127	107.8	0.039	0.162	0.315	1.234
11	19.85	5.1[1]	13.4	1045.5	138	102.1	0.055	0.147	0.490	1.313
12	21.31	6.1	12.4	1012.8	142	106.5	0.042	0.035	0.361	0.300
13	23.61	6.9	12.0	1009.8	145	114.4	0.015	0.028	0.129	0.238

(Continued)

TABLE 2. (continued).

Run Code	Moisture (%)	Orsat Analysis (%)		Exhaust Flow Rate (SCFM)	Stack Temp. F.	Isokinetic (%)	Concentration (gr/scf)		Emission Rate (lb/hr)	
		CO_2	O_2				Particulate	Chloride	Particulate	Chloride
14	23.36	6.3	12.5	1086.7	146	121.5	0.015	0.073	0.140	0.676
15	25.37	4.6[1]	13.9	1059.0	148	115.7	0.010	0.041	0.878	0.374
16	32.47	5.8	12.5	1037.9	153	123.2	0.038	0.009	0.339	0.081
17	17.89	6.0	13.4	1166.3	135	107.3	0.016	0.037	0.159	0.367
18	17.16	5.9	12.5	1261.0	130	107.2	0.020	0.045	0.215	0.487

[1] Orsat Analyses are suspected to be incorrect, probably due to a leakage in the system during that test.

TABLE 3. PARTICULATE AND CHLORIDE REMOVAL EFFICIENCIES: HYDRO-SONIC SCRUBBER

Configuration[a]	Run No.	Particulate Inlet (lb/hr)	Particulate Outlet (lb/hr)	Particulate Efficiency Percent	Chloride Inlet (lb/hr)	Chloride Outlet (lb/hr)	Chloride Efficiency Percent
SH/Lo/R	4[b]	3.905	0.968	75.2	22.65	0.294	98.7
	8	2.253	0.416	81.6	20.20	0.117	99.4
	Average			81.6			99.1
SH/Lo/F	5[c]	3.133	0.294	90.6	30.84	0.684	97.8
	6	4.168	0.269	93.5	30.85	0.281	99.1
	7	1.532	0.257	83.2	21.73	0.310	98.6
	9[d]	2.021	0.363	82.1	20.13	0.112	99.4
	Average			87.4			98.7
SH/Hi/R	1[d,e]	1.851	0.244	86.8	16.63	0.329	98.0
	2	4.598	0.438	90.5	21.98	0.206	99.1
	3	1.961	0.249	87.3	23.22	0.195	99.2
	Average			88.2			98.8
TN/-/R	16[f]	4.274	0.339	92.1	39.51	0.081	99.8
TN/-/F	10	3.664	0.315	91.4	29.37	1.324	95.5
	11	3.473	0.489	85.9	22.61	1.313	94.2
	12	1.962	0.361	81.6	19.28	0.301	98.4
	Average			86.3			96.0

(Continued)

TABLE 3.(continued).

Configuration[a]	Run No.	Particulate Inlet (lb/hr)	Particulate Outlet (lb/hr)	Particulate Efficiency Percent	Chloride Inlet (lb/hr)	Chloride Outlet (lb/hr)	Chloride Efficiency Percent
SS/-/F	13	2.056	0.129	93.7	17.88	0.238	98.7
	14	4.096	0.. 40	96.6	27.45	0.676	97.5
	15	4.173	0.087	97.9	18.55	0.374	98.0
	17	3.857	0.159	95.9	27.83	0.367	98.7
	18	2.632	0.215	91.8	30.70	0.487	98.4
	Average			95.4			98.3

[a] Configuration codes are: SH = Steam-Hydro; TN = Tandem Nozzle; SS = Supersub; Hi = High energy input; Lo = Low energy input; - = Not applicable to this version; Fresh = Freshwater used in APCD; R = Recycle water from ENSCO scrubber used in APCD.

[b] Inlet train post-test leak check unacceptable.

[c] Broken inlet frit during run: test stopped.

[d] Broken frit during inlet post-test leak check.

[e] Outlet impinger overflow; moisture and Cl probably low.

[f] Inlet impinger spilled during sample recovery.

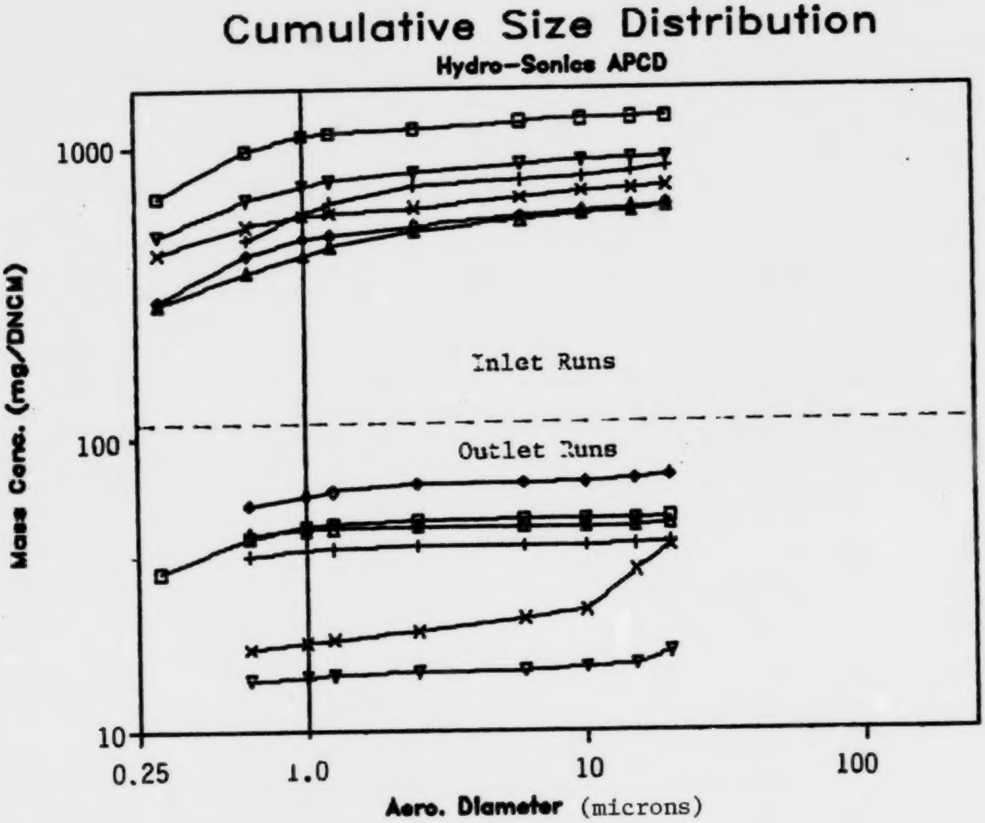

Figure 5. Cumulative particle concentration vs. particle diameter: Hydrosonics APCD.

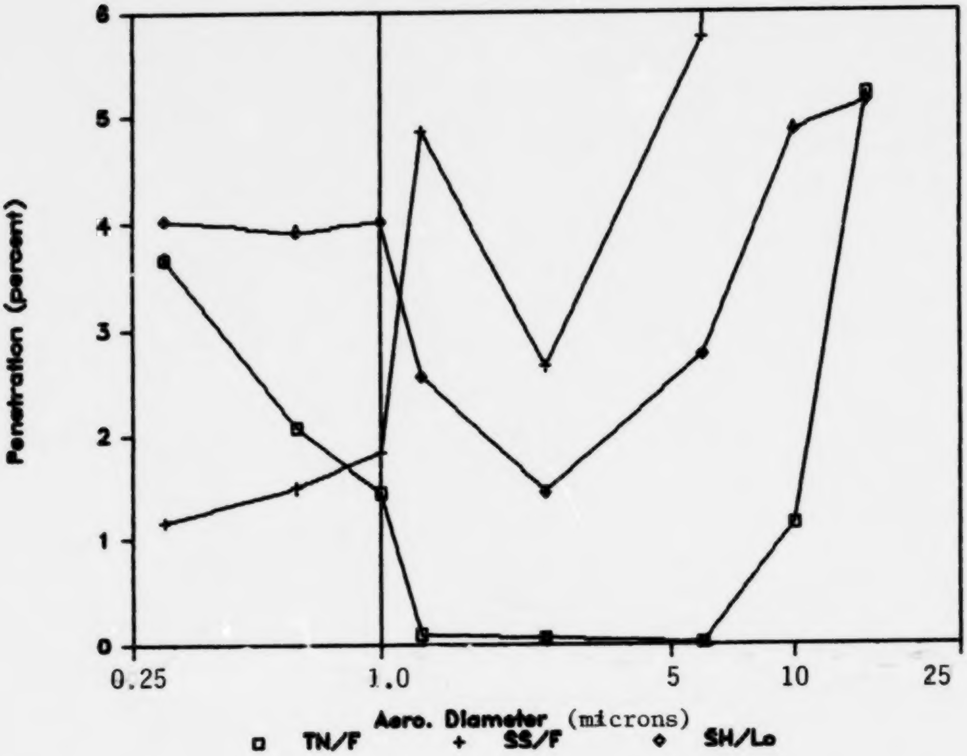

Figure 6. Percent particles passing through APCD vs. particle diameter.

TABLE 4. COMPARISON OF FINE PARTICLE (<1 MICRON) ENRICHMENT FACTORS (OUT/IN) FOR VARIOUS OPERATING CONDITIONS

Operating Condition	Inlet Impactor Run No.	Percent of Mass <1 Micron	Outlet Impactor Run No.	Percent of Mass <1 Micron	Out/In
SH/Lo/F	2	43	3	69	1.6
SH/Lo/F	3	57	4	67	1.2
TN/- /F	4	38	5	60	1.6
SS/- /F	5	64	6	36	0.6
SS/- /F	6	70	7	26	0.4

On the basis of this information the SuperSub configuration is more effective at removing these fine particles than either the Steam-Hydro or Tandem Nozzle configurations. This is an important consideration when the polluted gas stream contains particles which are predominantly less than 1.0 micron.

CONCLUSIONS

1. The Steam-Hydro, Tandem Nozzle, and SuperSub Model 100 versions of this scrubber system are all capable of over 99 percent removal of

   HCl from exhaust gas formed during incineration of chlorinated hazardous wastes. Sufficient alkalinity should be added to the scrubber water to neutralize the absorbed HCl.

2. There is no statistically significant difference in the particulate removal efficiency of Steam-Hydro operating at high energy input and the Tandem Nozzle version for the particle size distributions encountered in these tests.

3. The SuperSub Model 100 has the highest particulate removal efficiency and best capture of submicron particles of the three Hydro-Sonic units tested on this particular emission source.

4. The Steam-Hydro has the highest power consumption and the lowest water usage of the three units.

5. The SuperSub has a low power consumption but a high water usage.

SECTION 5

ETS, INC. DRY SCRUBBER

GENERAL DESCRIPTIONS

This patented dry scrubbing system was originally developed by Grant Hollett (Energy and Pollution Controls, Inc.). ETS, Inc. purchased all rights and interests in the system in 1982. They are currently continuing development of this unit.

The system was initially developed (and is principally marketed) as an alternative to wet scrubbers for flue gas desulfurization. In May of 1980, the unit achieved the first successful treatment of the very visible and chemical laden gases from the manufacture of common bricks. The tests, sponsored by the Flick-Reedy Corporation, demonstrated the units capability of over 90 percent SO_2 removal.

ETS, Inc. conducts research on a prototype unit installed at their Travelers Rest, SC facility. Greater than 95 percent SO_2 removal has been attained in these tests. The system, which uses finely pulverized hydrated lime for acid gas capture, appears to have several advantages over conventional wet scrubbers. These include: lower energy consumption, fewer corrosion problems, simpler hardware, less maintenance, and better flue gas heat utilization. The system also may be as much as 50 percent less expensive than a wet scrubber to install and operate.

The unit has two major components: the dry reactor and a particulate collection device. The patented dry reaction (see Figure 7) has a number of unique components. The basic operating principals are as follows. Flue gas is directed cyclonically into the reactor. The rotating slinger unit (driven by a hydraulic motor) delivers the dry reactant (usually 200 mesh hydrated lime) perpendicular to the flue gas flow. This creates maximum mixing and intimate contact of the reactant and pollutants. An internal recirculator, with no moving parts, is located above the slinger. This device increases the contact time and enhances removal of the acid gases. The slinger then directs the dry reaction products down and into an expansion section where the larger particles are removed. The finer particulate matter is carried into the particulate collection device.

The particulate collector can be a conventional baghouse, an electrostatic fabric filter (ESFF) baghouse, or a Reduced Entrainment Precipitator (REP) developed by ETS. The lime dust entrained in the flue gas continues to react with acid gas components throughout the transport ductwork. In addition, the lime dust aids in building a reactive filter cake on the fabric filters. This serves two purposes. First, reaction with acid gas

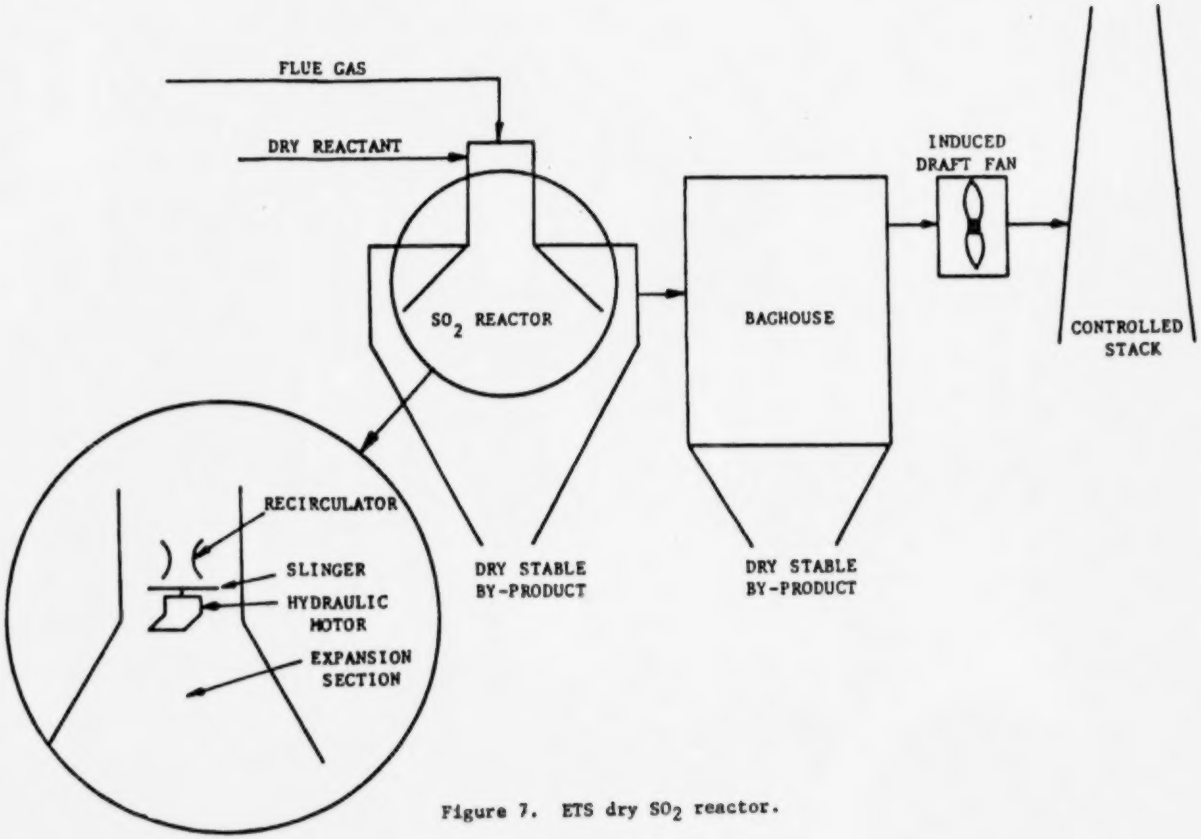
FLUE GAS
DRY REACTANT
SO$_2$ REACTOR
BAGHOUSE
INDUCED DRAFT FAN
CONTROLLED STACK
DRY STABLE BY-PRODUCT
DRY STABLE BY-PRODUCT
RECIRCULATOR
SLINGER
HYDRAULIC MOTOR
EXPANSION SECTION

Figure 7. ETS dry SO_2 reactor.

components continues until final particulate removal occurs. Secondly, the precoat assists in removing the fine particulate without excessive pressure drops across the filters.

This system is totally dry. The reactants are delivered as dry powder, not as a slurry required for the spray dryer type scrubbers. The reacted product is also a dry powder and can be handled much as one handles dust collected in a baghouse. Since no water is used at any point in the system, there is no mist carryover problem, little or no corrosion in the exhaust stack which remains dry and minimum loss of stack gas buoyancy since this energy is not used to evaporate water.

UNIT TESTED

The unit tested is the prototype research unit that ETS removed from their Travelers Rest, SC research facility. This unit has a rated capacity of 2000 ACFM. The cone shaped dry reactor has a maximum outside diameter of 1.2 meters (4 feet). Total height is 2.6 meters (8.5 feet).

The dry scrubber was connected to a pulse jet baghouse which used Nomex® fabric cartridges. An induced draft fan was located at the outlet of the baghouse forcing the cleaned gas into the 30 cm (12-inch) I.D. vertical exhaust stack. Shown in Figure 8 is the general arrangement of the components during this test.

This particular unit is not designed to be portable. Considerable work was required to install the system. Ductwork leading to and from the baghouse had to be fabricated. Insulation was applied to parts of the system to prevent excessive heat loss. All identified system leaks were repaired.

TEST RESULTS

The ETS system was installed during the last week of March 1984. The system was operated and tested during two separate periods, April 1-10 and April 23-26, 1984. Two reactant materials, hydrated lime and nahcolite were evaluated for HCl removal effectiveness.

The hydrated lime used is a commercially available material supplied by Arkansas Lime, Batesville, Arkansas. Nacholite was obtained from the Bureau of Mines. Chemical analyses of these materials is given in Table 5. Each of these materials was fed into the dry reactor at two rates, 0.27 kg/min and 0.54 kg/min (0.6 and 1.2 lb/min). Since the HCl concentration in the flue gas varied and because different flue gas flow rates were used, these feed rates allowed a variety of reactant/HCl stoichiometric ratios to be evaluated.

The ENSCO plant shut down for required maintenance during this test. Thus, two test periods were required to achieve the planned program. Given in Table 6 is a comparison of several relevant parameters for these two test periods.

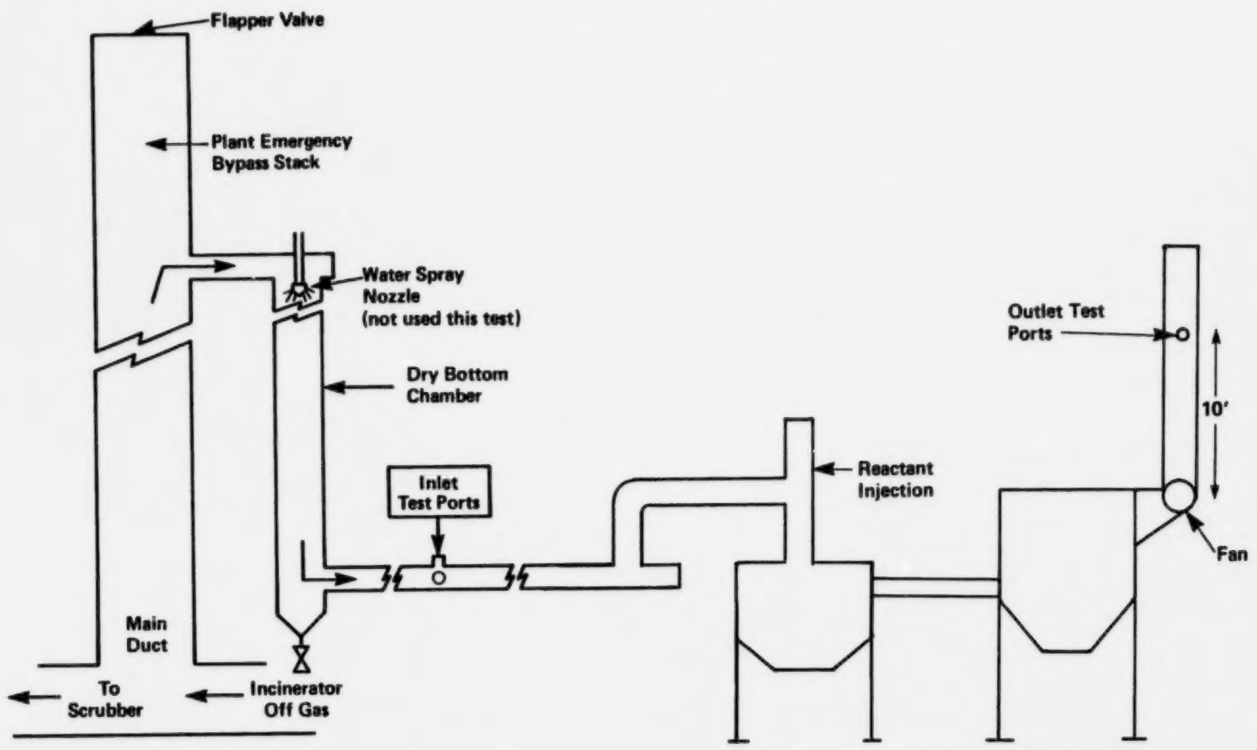
Flapper Valve
Plant Emergency Bypass Stack
Water Spray Nozzle (not used this test)
Dry Bottom Chamber
Inlet Test Ports
Reactant Injection
Outlet Test Ports
10'
Fan
Main Duct
To Scrubber
Incinerator Off Gas
Dry Reactor
Baghouse

Figure 8. General relationship of sampling ports and major components of the ETS system.

TABLE 5. CHEMICAL COMPOSITION OF MATERIAL USED IN ETS TESTS

Material	Percent by Weight
Hydrated Lime	
$Ca(OH)_2$	94.75
$CaCO_3$	1.36
Water	0.56
Inerts	3.33
Nahcolite	
$NaHCO_3$	52.76
$NaCO_3$	3.5
NaCl	0.49
Na_2SO_4	0.4
Na_2SO_3	0.001
$NaNO_3$	0.02
Insolubles	40.86
Water	1.83

Both materials were 100% - 200 mesh.

TABLE 6. INLET SITE COMPARISON DATA[1]

	ETS-I	ETS-II
Percent moisture	9.2 (2.3)	10.1 (4.7)
Percent CO_2	3.3 (0.5)	3.5 (0.3)
Percent O_2	16.7 (0.6)	16.9 (0.1)
Flow rate (SCFM)	280.0 (55.0)	392.0 (63.0)
Stack temperature (°F)	474.0 (90.0)	594.0 (82.0)
Conc. particles (gr/SCF)	0.85 (0.58)	9.30 (0.11)
Conc. chloride (gr/SCF)	5.3 (1.6)	4.3 (1.4)

[1] Averages and (standard deviations) shown for indicated parameters: ETS-I refers to testing 4/4/84 through 4/10/84 (Runs 1-10); ETS-II refers to testing 4/24/84 through 4/26/84 (Runs 11-16).

Given in Table 7 are the particulate and HCl removal efficiency data for the two reactants at the various stoichiometries. More detailed summary test data is given in Tables 8 and 9. Six of the nine tests using lime as the reactant indicate an HCl removal efficiency of over 98 percent. Only one of the tests using nahcolite achieved over 90 percent HCl removal.

The relationship of HCl removal efficiency and the stoichiometric ratio (SR) of the two reactants, lime and nahcolite, is shown in Figure 9. The stoichiometric ratios were calculated from the ETS reported feed rates, reactant analysis, and Method 5 HCl data assuming reaction of HCl with the active species ($CaCO_3$ and $Ca(OH)_2$ for lime, and $NaHCO_3$ and Na_2CO_3 for nahcolite). The stoichiometric ratio ranges from 2 to 9 for the tests in which lime was the reactant. It appears from the plot of the data that the SR for lime must be nearly 3:1 to insure scrubbing efficiencies of 99 percent. On a weight basis, this implies that the lime feed rate must approximately equal the HCl inlet rate to achieve the desired emission control.

Due to limitation in the feed equipment, nahcolite was injected at much lower stoichiometric ratios. Thus, it is not possible from the data to compare HCl removal efficiencies at equivalent lime and nahcolite stoichiometric ratios. The HCl removal efficiency does not appear to correlate with the nahcolite/HCl stoichiometric ratio up to a ratio of 1.7. Therefore, from these tests, it is not possible to determine the nahcolite/HCl ratio required to achieve 99 percent HCl removal. It is not known if the high percentage (∿44) of inerts affected the reactivity of the material.

Given in Table 7 are the removal efficiencies for total particulate matter. These efficiencies are calculated strictly from the Method 5 data. No allowance has been made for the reactant materials added in the dry reactor. For most of the runs, the weight of reactant added ranged from about 40 percent to over 100 percent of the weight of particulate entering the system from the incinerator. The reactants added were 100 percent less than 200 mesh (74 microns). Obviously some of the material was much smaller and may have passed through the baghouse.

The calculated efficiencies for the first 10 runs were all greater than 90 percent with most in the 95 to 98 percent range. It should be noted that, due to the bias toward smaller particles caused by the slipstream sample withdrawal, this is the removal efficiency for the finer particles in the ENSCO incinerator exhaust gas. Since the unit would be expected to remove the larger particles more easily, the removal efficiency for the total gas stream would be expected to be even higher.

It is suspected that the low efficiencies measured for Runs 11 through 16 were due to persistent difficulties in sealing the cartridges in the baghouse. In addition, a tear was discovered in one cartridge after Run 11. We do not believe, therefore, that the particulate removal efficiencies reported for Runs 11 through 16 accurately reflect the particulate removal capabilities of the unit.

The particulate control capability of the ETS unit as a function of particle size was also determined. The cumulative (see Figure 10a) and

TABLE 7. SUMMARY RESULTS: ETS UNIT

Reactant used	Stoichiometric ratio	Run Number	HCl Inlet (lb/hr)	HCl Outlet (lb/hr)	HCl Efficiency percent	Particulates Inlet (lb/hr)	Particulates Outlet (lb/hr)	Particulates Efficiency percent
Lime	2.80	1	23.03	0.310	98.7	1.390	0.124	91
Lime	4.53	2	14.54	1.597	89.0	1.609	0.043	97
Lime	4.50	3	14.65	0.293	98.0	1.710	0.065	96
Lime	6.61	4	9.98	0.082	99.2	0.873	0.046	95
Lime	8.71	5	7.57	0.086	98.9	0.792	0.041	95
Lime	8.07	6	8.17	0.036	99.6	3.492	0.058	98
Lime	5.29	7	6.23	0.013	99.8	0.748	0.074	90
Lime	1.94	8	16.99	7.432	56.3	1.627	0.039	98
Lime	2.42	9	13.59	2.847	79.1	5.295	0.104	98
Nahcolite	0.70	10	12.58	0.850	93.2	2.502	0.100	96
Nahcolite	0.53	11	16.43	2.957	82.0	1.612	3.920	(1)
Nahcolite	0.87	12	10.12	4.580	54.7	1.765	0.424	76
Nahcolite	-	13	(2)	7.252	(2)	1.215	0.301	75
Nahcolite	0.56	14	15.59	7.206	53.8	1.511	0.228	85
Nahcolite	1.73	15	10.72	3.423	68.1	0.778	0.135	83
Nahcolite	0.98	16	18.80	12.576	33.1	0.918	0.567	38

[1] Torn baghouse cartridge

[2] Sample bottle broken and sample lost before analysis.

TABLE 8. BAGHOUSE INLET SUMMARY OF TEST RESULTS

Run Code	Moisture (%)	Orsat Analysis (%)		Exhaust Flow Rate (scfm)	Stack Temp. (°F)	Isokinetic (%)	Concentration (gr/scf)		Emission Rate (lb/hr)	
		CO_2	O_2				Particulate	Chloride	Particulate	Chloride
EI-04-1[a]	10.43	2.4	11.4	339.3	540	87.2	0.478	7.920	1.3904	23.0281
EI-04-2[a]	5.86	2.8	12.5	278.8	618	82.7	0.673	6.090	1.6086	14.5420
EI-04-3[a]	13.77	2.4	11.4	278.1	535	89.8	0.717	6.150	1.7097	14.6476
EI-05-4[a]	7.47	4.7	14.7	244.9	464	87.3	0.417	4.760	0.8750	9.9837
EI-05-5	8.45	3.3	16.9	194.8	457	90.3	0.474	4.530	0.7919	7.5713
EI-05-6	7.73	3.7	16.1	272.0	385	83.6	1.500	3.510	3.4919	8.1725
EI-06-7	7.21	3.2	16.2	307.6	345	93.3	0.284	2.360	0.7483	6.2290
EI-10-8	9.79	2.5	17.7	370.5	559	97.3	0.512	5.350	1.6267	16.9886
EI-10-9	9.78	3.9	16.1	311.0	478	90.9	1.990	5.100	5.2948	13.5912
EI-10-10	11.38	3.0	17.0	207.7	363	99.2	1.410	7.070	2.5023	12.5841
EI-24-11	18.12	3.4	16.9	517.3	683	97.0	0.364	3.710	1.6118	16.4313
EI-25-12	5.56	3.4	16.9	384.6	604	95.5	0.535	3.070	1.7646	10.1211
EI-25-13[a]	8.38	4.1	17.1	364.2	660	100.1	0.389	b	1.2151	b
EI-25-14	10.24	3.4	16.9	350.8	555	96.1	0.503	5.180	1.5108	15.5858
EI-26-15	12.55	3.4	16.9	385.1	453	104.1	0.236	3.250	0.7783	10.7201
EI-26-16	6.01	3.4	16.9	352.5	611	107.9	0.304	6.230	0.9178	18.8044

[a] Orsat data considered suspect. Average orsat values were used for computer entry and data calculation.
[b] Sample bottle was broken before sample was analyzed.

TABLE 9. BAGHOUSE OUTLET SUMMARY OF TEST RESULTS

Run Code	Moisture (%)	Orsat Analysis (%)		Exhaust Flow Rate (scfm)	Stack Temp. (°F)	Isokinetic (%)	Concentration (gr/scf)		Emission Rate (lb/hr)	
		CO_2	O_2				Particulate	Chloride	Particulate	Chloride
EO-04-1[a]	6.86	2.3	12.1	686.5	178	98.7	0.0211	0.0527	0.1240	0.3100
EO-04-2[a]	4.84	2.7	13.7	568.5	194	97.3	0.0088	0.3280	0.0429	1.5971
EO-04-3	5.22	1.7	18.7	669.9	164	96.6	0.0113	0.509	0.0651	0.2925
EO-05-4	4.54	2.1	18.5	628.2	162	100.4	0.0085	0.0152	0.0455	0.0820
EO-05-5	5.39	1.8	18.3	627.6	148	104.4	0.0076	0.0159	0.0406	0.0857
EO-05-6	5.95	1.7	18.5	524.0	151	99.6	0.0130	0.0079	0.0584	0.0355
EO-06-7	4.28	1.4	19.1	514.1	129	97.1	0.0168	0.0030	0.0740	0.0133
EO-10-8	6.50	2.8	17.0	677.5	214	101.6	0.0067	1.2800	0.0389	7.4234
EO-10-9	5.30	2.1	18.3	521.5	195	101.8	0.0232	0.6370	0.1039	2.8466
EO-10-10	5.80	2.8	18.0	383.9	143	102.3	0.0304	0.2580	0.0998	0.8498
EO-24-11	14.86	3.6	17.4	719.8	301	108.8	0.6350	0.4790	3.9204	2.9566
EO-25-12	5.04	2.9	17.9	694.7	202	96.9	0.0712	0.7690	0.4236	4.5798
EO-25-13	9.18	3.6	16.8	505.3	236	112.2	0.0696	1.6700	0.3013	7.2524
EO-25-14	7.12	2.9	18.1	453.1	219	107.8	0.0586	1.8600	0.2275	7.2058
EO-26-15	10.14	3.1	16.9	612.7	216	105.9	0.0258	0.6520	0.1354	3.4226
EO-26-16	8.34	3.5	16.9	547.3	225	105.0	0.1210	2.6800	0.5674	12.5758

[a] Orsat data considered suspect. Average orsat values were used for computer entry and data calculation.

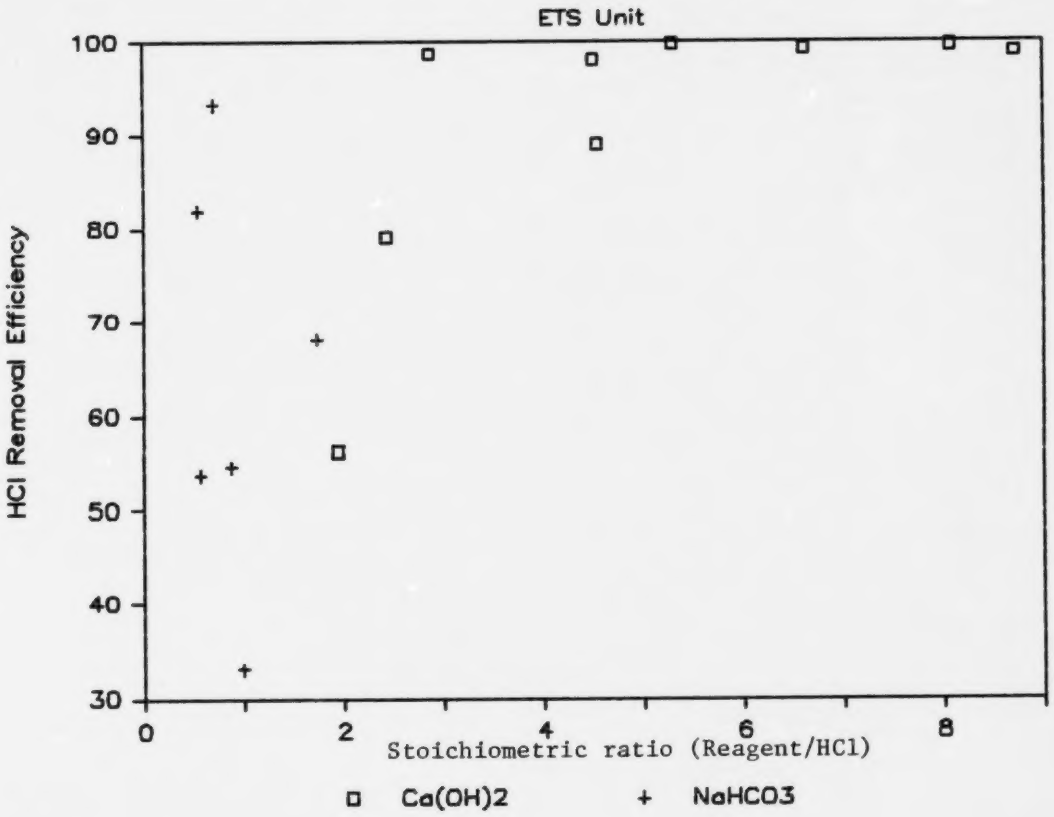

Figure 9. HCl removal efficiency: ETS unit.

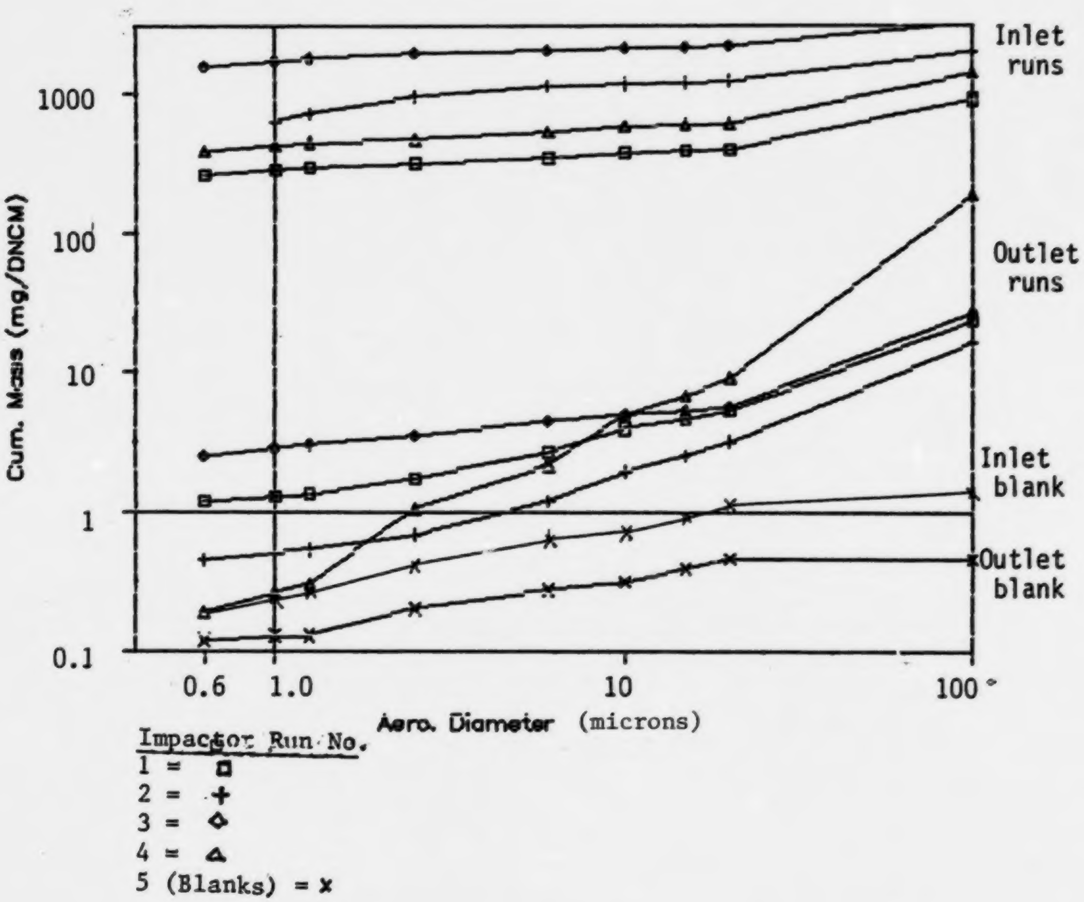

Figure 10a. Cumulative particle mass versus particle diameter.

differential (see Figure 10b) mass distribution for the four sampling runs and a blank impactor run set were calculated. Comparison of inlet and outlet run data (as in removal efficiency calculations) should be done with caution due to sampling time differences (both in overlap and duration).

The relatively high and increasing (with each succeeding run) concentration of particles below 2 microns in size is evident in Figures 9 and 10. The excellent removal efficiency (>99 percent) for small diameter particles is evident in these figures and is plotted in Figure 11. The relatively poorer calculated removal efficiencies (still above 95 percent) for 5 microns and larger particles is likely due to the small amount of large particles and errors resulting from differences between large numbers. The increase in dust loading due to injection of lime may also account for this apparent anomaly.

Shown in Table 10 are the percentages of particulate matter less than 1 micron in size in the inlet and outlet samples. This also implies better removal of fine particulate than coarse particulate. This is counter to the expected performance of a fabric filtration system. In our opinion, these data imply that a significant fraction of the particulate matter in the unit exhaust originated with the lime feed.

DIFFICULTIES ENCOUNTERED

There was a great deal of heat loss through the system. Because of these losses baghouse temperatures were routinely below those that would be recommended for reliable system operation. It is believed that these low temperatures were at least in part responsible for some of the baghouse operational problems experienced during the test program. Operation at temperatures less than 260°F should provide low chloride emissions, however, at the same time cause high levels of $CaCl_2$ to be present in the filter cake. $CaCl_2$ is hygroscopic, thus causing bag cleaning problems resulting in high pressure drop and low gas flow.

Operation at higher baghouse temperatures ($\approx$320°F) might have alleviated this problem. This was not possible due to inadequate insulation on the reactor, connecting ductwork and baghouse.

CONCLUSIONS

1. The ETS dry scrubber/baghouse combination is capable of over 99 percent removal of HCl from the exhaust gas of incinerators burning chlorinated hazardous wastes.

2. A high rate of reagent (lime) feed, at least three moles of hydrated lime per mole of HCl, was required to achieve satisfactory HCl removal. Recycle experiments to determine if the lime utilization could be improved were not attempted.

3. The ETS unit demonstrated over 95 percent removal of the particulate matter from the emission source tested.

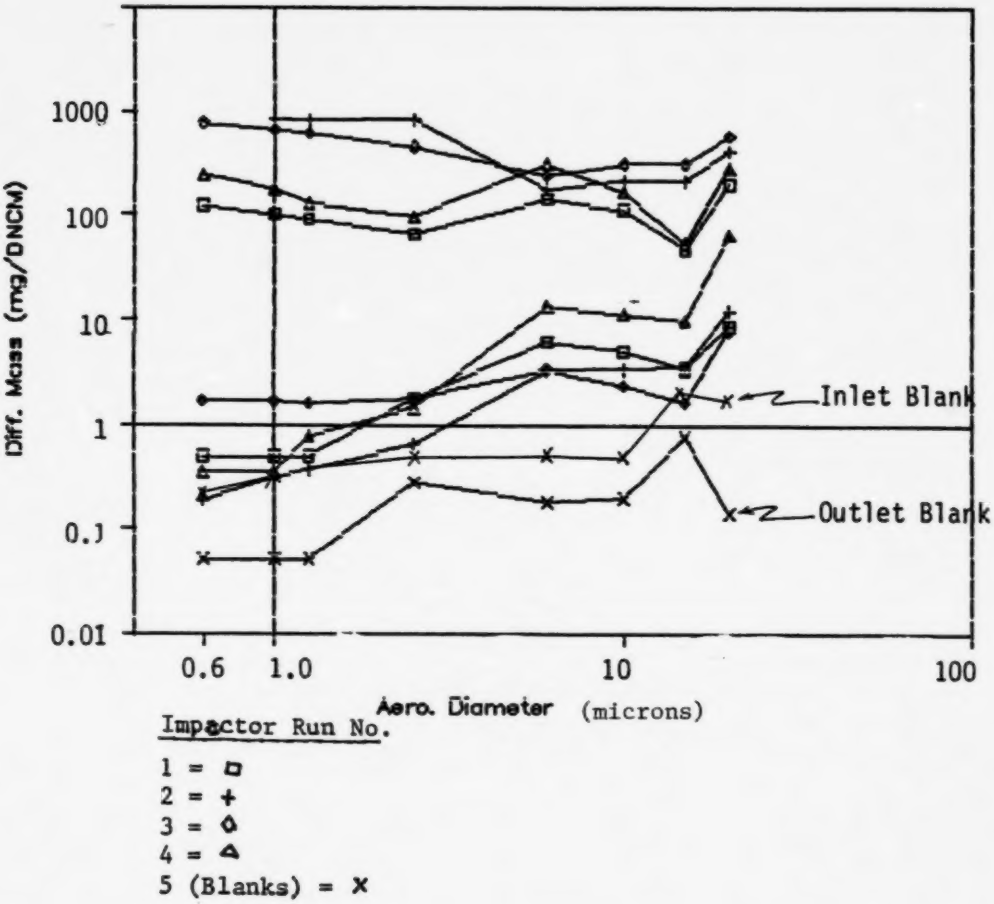

Figure 10b. Differential particle mass vs. particle diameter.

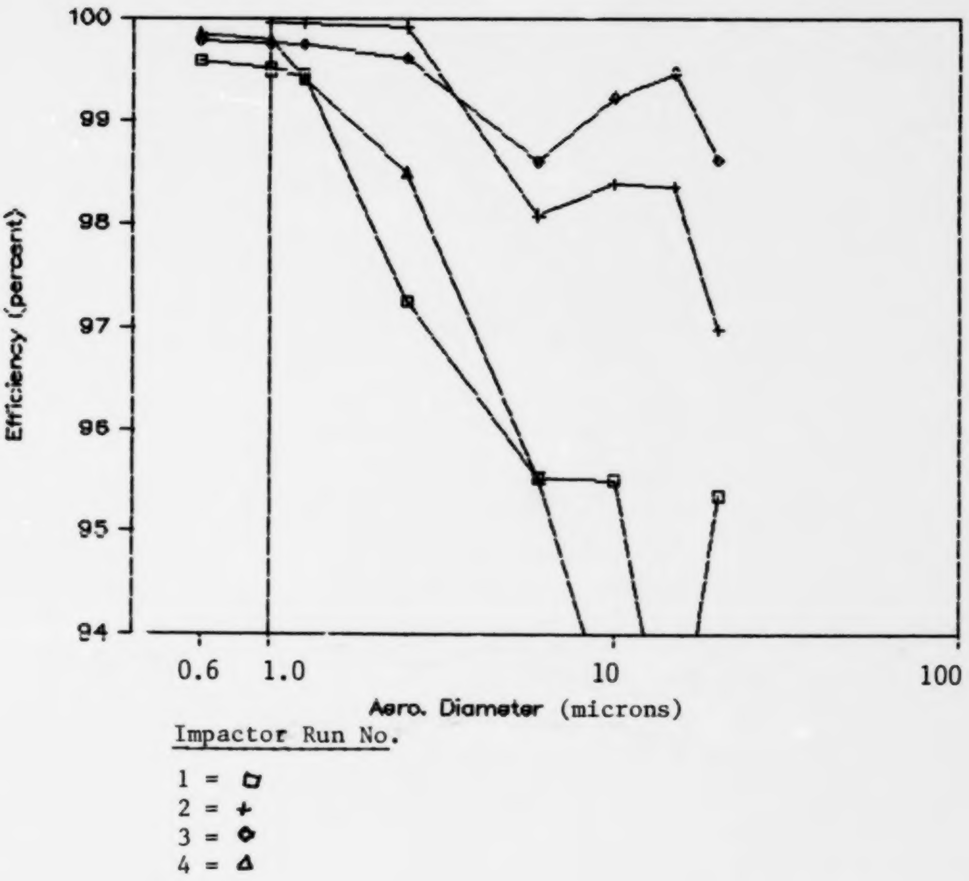

Figure 11. Size-based particle removal efficiency: ETS unit.

4. The unit experienced no operating problems due to variation in plant operating conditions or from the sticky particulate in the exhaust gas.

5. The unit, as currently configured, has no provision to control the reagent feed in relation to fluctuating concentrations of acid gas. Thus, to insure high HCl removal efficiency, an excess of reagent must always be used.

TABLE 10. COMPARISON OF FINE PARTICLE (<1 MICRON) ENRICHMENT FACTORS OUT/IN FOR ETS IMPACTOR RUNS

Inlet run Number	Percent (<1 micron)	Outlet Run number	Percent (<1 micron)	Out/In
1	31.4	1	5.26	0.17
2	31.7	2	3.01	0.09
3	52.6	3	10.2	0.19
4	30.7	4	0.14	0.004

SECTION 6

VULCAN ENGINEERING COMPANY HI-TAC FILTER

GENERAL DESCRIPTION

The high temperature air cleaning (HI-TAC) device was developed by Vulcan Engineering Company for the removal of particulate matter from gas streams at higher collector inlet temperatures than previously possible. Although the HI-TAC unit looks much like a conventional baghouse, there are substantial differences.

The filter media is entirely metallic. This results in greater resistance to moisture, temperature, corrosion, abrasion, and pressure than is provided by conventional fabric media. Although temperatures below 500°F do not decrease the collection efficiency, the media is designed to operate in the 600°F to 1350°F range. Temperature excursions to 2000°F can be tolerated. The filter elements will even tolerate flame temperatures.

The filter media can operate at appreciably higher air-to-cloth ratios (15:1 and greater) than conventional baghouses. The higher air-to-cloth ratio means fewer filter elements and, therefore, less space requirements than conventional systems. The smaller size and increased heat resistance also allows the unit to be placed close to the emission source. Because the filter can operate effectively over a broad range of air-to-cloth ratios, it is a very forgiving collector. Wide swings in gas flow due to process changes or expansion of the physical plant can generally be accommodated without increasing the size of the filter unit.

The unit was developed for use in the iron and steel industry to control particulate from the many high temperature sources. The initial tests on the unit were performed on exhaust gas from an iron cupola. The gas entering the unit was 750°F and contained 1.39 grains of particulate per dry standard cubic foot (dscf). The unit operated with an air-to-cloth ratio of 16:1 and collected 99.2 percent of the particulate.

Additional tests were performed on exhaust gas from a hot iron desulfurization station at a Canadian steel firm. At an inlet gas temperature of 350°F and particulate loading of 6.13 grains/dscf, the unit collected 98 percent of the fume while operating at an air-to-cloth ratio of 15:1.

This project represents the first test of this unit at a hazardous waste incinerator. Because the gas temperatures from these processes are high (over 1000°F), conventional baghouses are seldom used. Where they are used, considerable additional expense is incurred due to large radiation-convection ductwork to cool the gas or increase baghouse size to handle additional cooling dilution air added to moderate the gas temperature. The HI-TAC unit, offering both high filtration rates and high temperature operation, seemed to be ideally suited to this application.

UNIT TESTED

The unit tested is completely portable and self-contained. Connection to an electrical power source and the exhaust duct are the only setup requirements. The unit (see Figure 12) is mounted on a Talbert 47-ft double drop Tandem axle trailer. Mounted on the trailer are four manifolded banks of insulated separator modules, an electric motor driven exhaust fan, cleaning device and dust conveyor drives, a 6 ft x 7 ft control room, a duplex air compressor, an air dryer, an instrument control center, insulated inlet and exhaust ductwork, access platforms and a catwalk. The ductwork is equipped with ports for gas sampling by EPA Method 5. The maximum width and height are 8 feet and 12 feet 4 inches, respectively. The entire system gross weight is 42,000 lb. With all four compartments operating, the unit capacity is 8,000 ft^3/min of exhaust gas.

Each of the four cleaning modules houses four removal cartridge elements. Each element consists of a metallic reinforcing framework covered with stainless steel mesh. The weave may be varied to determine appropriate design for a particular source. An induced draft fan, located at the cleaning modules outlet manifold provides gas motive force. A programmable controller activates the filter cleaning devices. These include air knives and vibrators on two modules, and pulsers and rappers on the other two modules. The cleaning cycle may be linked to specified operating periods or to module pressure drop. Manual cycling is also permitted.

An additional vertical exhaust stack, see Figure 13, was installed on the trailer to relieve some of the difficulty involved with sampling a horizontal duct. This location was used for Runs 1 through 8. For Runs 9 and 10, outlet sampling was conducted in the horizontal duct on the trailer. A water spray was installed in the vertical stack to reduce HCl emissions. The Hi-Tac unit is not designed nor equipped to control acid gases.

TEST RESULTS

Shown in Table 11 are the averages and standard deviations of several parameters measured at the inlet sampling location during these tests. Several of these exhibit substantial variation, also noted during testing of the other units described in this report. For example, the gas temperature measured at this point ranged from 650°F to 865°F. Since similar variability was noted on ENSCO's process control instruments, it is felt that this variability will have to be accommodated by any control device used on this type source.

HI-TAC OPERATING CONDITIONS

During this test program, there were three (3) types of weaves in the unit. These were:

Module I - 150 x 105 plain weave
Module II - 325 x 325 twilled weave

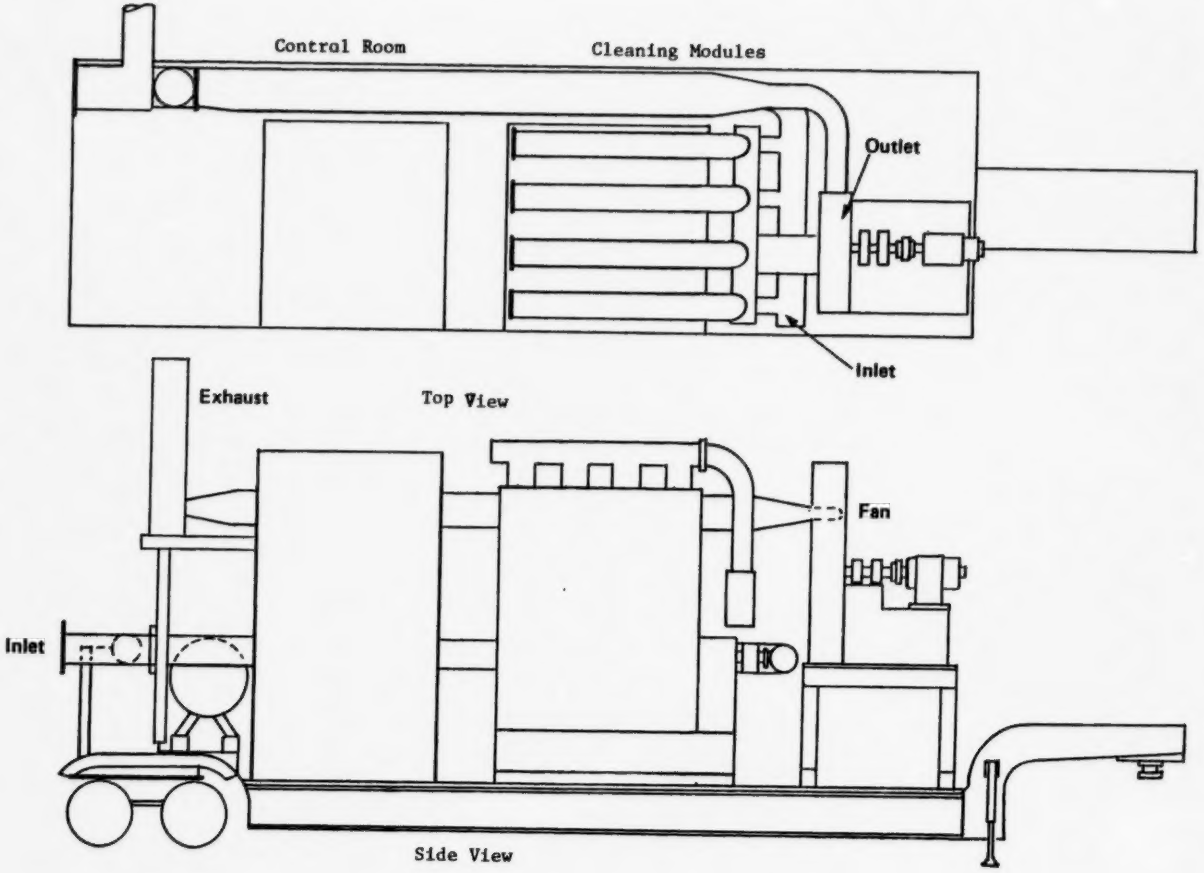
Control Room
Cleaning Modules
Outlet
Inlet
Exhaust
Top View
Fan
Inlet
Side View

Figure 12. Schematic of Vulcan Hi-Tac mobile unit.

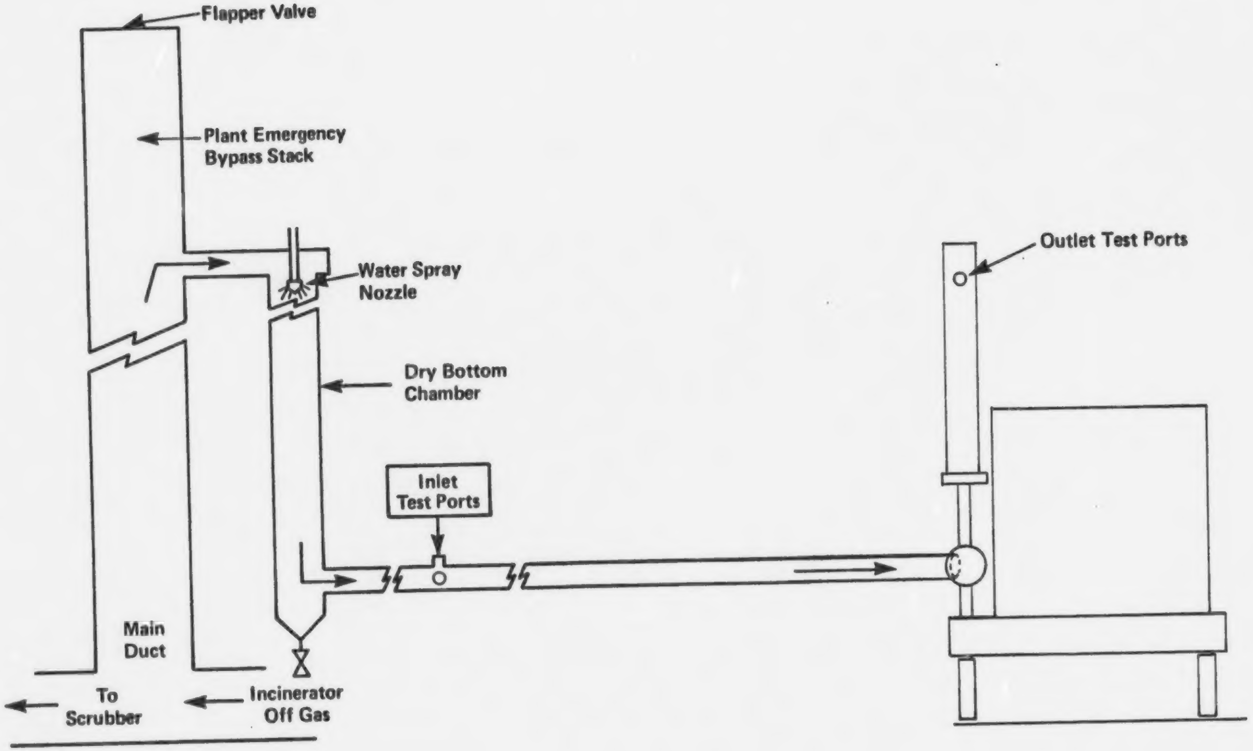
Flapper Valve
Plant Emergency Bypass Stack
Water Spray Nozzle
Dry Bottom Chamber
Inlet Test Ports
Outlet Test Ports
Main Duct
To Scrubber
Incinerator Off Gas

Figure 13. General relationship of sampling ports and major components of the Vulcan system.

TABLE 11. INLET SITE GENERAL DATA[1]

	Vulcan Unit
Percent moisture	19.3 (3.0)[2]
Percent CO_2	6.2 (1.3)
Percent O_2	12.8 (1.4)
Flow rate (SCFM)	528.0 (131.0)
Stack temperature (°F)[3]	750.0 (75.0)
Concentration particles (gr/SCF)	0.70 (0.25)
Concentration chloride (gr/SCF)	5.9 (1.8)

[1] Averages and (standard deviations) shown for indicated parameters.

[2] Omitting Run 1 as outlier--more than 3 standard deviation from listed mean.

[3] Dry bottom quench inactive for this test.

Module III and IV - 50 x 250 dutch weave

Given in Table 12 is a summary of the unit operating conditions. Much detail is provided in the Vulcan Engineering Company test report in the Appendices.

The total removal efficiencies for particulate matter and chloride are shown in Table 13. Summaries of important test data are given in Table 14 for the inlet site and in Table 15 for the outlet site.

As can be seen, removal efficiency for particulate matter is quite erratic, varying from 34 percent to 98 percent. Excluding run number 1, the average removal efficiency is 89.7 percent. Inspections of the cartridges before and after test runs indicated that cake formation on the filter fabric was not reliable. During several inspections following cartridge cleaning, it was observed that a very large portion (about 70 percent) of the fabric surface was still covered by the filter cake, with about 20 percent of the surface clean down to the fabric. The sticky particulate from the incinerator interfered with proper cake formation and filter cleaning. It is possible that fabric weave changes or precoating of the fabric might correct this difficulty. The test program was not designed to adequately explore these options.

The unit did not demonstrate effective control of HCl. This is not surprising since the unit was not designed for this purpose. The small amount of lime used as filter precoat was not effective.

Particulate removal versus gas flow rate through the APCD (Figure 14) and particulate removal versus air-to-cloth ratio (Figure 15) show no clear trends. It is suspected that the peculiar cake formation properties and resultant filter cleaning problems have made these standard plots of little value.

Recognizing the difficulties cited above for particulate control, we have attempted to assess, with much trepidation, the removal efficiency at various particulate size ranges. The cumulative (Figure 16) and differential (Figure 17) mass concentration distributions for two inlet, two outlet, and the blank outlet runs were plotted. Inlet run number 2 (5/18/84) was not included since it had an unreasonably large (360 mg) mass increase on the filter which influences the entire distribution determined. The differential mass distribution for outlet run number 2 is also distorted due to an unreasonably large mass increase on Stage 1.

An efficiency distribution (Figure 18) was constructed using data from inlet run number 1, averaged with the lower three standard points from inlet run number 3. The outlet distribution was calculated using the average of data from runs 2 and 3 for the lower five standard diameters and the value from run 3 at 10 microns.

These data indicate 90 percent or better control of particles of less than 1 micron but decreasing efficiency as the particle size increases.

TABLE 12. HI-TAC UNIT OPERATING CONDITIONS

Variable	Run number									
	1	2	3	4	5	6	7	8	9	10
Filter area (ft^2)	216	216	216	216	162[1]	162	162	162	162	162
Air/cloth ratio	8.8	8.30	8.8	6.94	8.02	6.07	6.79	7.41	9.26	10.5
Filter type[2]	A	A	A	A	B	B	B	B	B	B
Lime injection	500 grams every 15 minutes	Precoat	500 grams every 15 minutes	Precoat	Precoat	Precoat	Precoat	900 grams every 10 minutes	Precoat	Precoat
Cleaning service[3]	None during test	K,P	None during test	None during test	K,P	None during test	None during test	K,P	None during test	None during test
Pressure (psi)	-	100	-	-	100	-	-	100	-	-
Duration	-	1 rev K 3 pulses of 1 sec	-	-	1 rev K 3 pulses of 1 sec	-	-	1 rev K 3 pulses of 1 sec	-	-
Frequency	-	15 min	-	-	30 min	-	-	5 min	-	-
Total pressure drop inches H_2O	34-34.5	25.5-25.5	31-34.5	33.8-34.5	30.0-31	33.5-34.5	32.3-36.0	35.0-36.5	36.3-39.0	31.0-32.5
Corrected pressure drop[4] inches H_2O	13-16.5	6.5-7.5	10.5-12.0	15.8-16.5	6.0-7.0	9.5-10.5	11.5-12.0	11.0-12.5	12.3-15.0	7.0-8.5

[1] Module 2 removed from service due to filter element failure.

[2] A = 25 percent 150 x 150 plain square, 25 percent 325 twill, 50 percent x 250 Dutch.
B = 33 percent 150 x 150 plain square, 66 percent 50 x 250 Dutch.

[3] K = air knife in modules 1 and 2; P = air pulse in modules 3 and 4.

[4] Corrected for inherent unit pressure drop. The row gives the pressure drop due to filter cake.

TABLE 13. VULCAN HIGH TEMPERATURE BAGHOUSE EFFICIENCY SUMMARY

		Particulates			Chlorides			
Run number	Date	Inlet Loading (lb/hr)	Outlet Loading (lb/hr)	System Efficiency (Percent)	Inlet Loading (lb/hr)	Outlet Loading (lb/hr)	System Efficiency (Percent)	Lime Injection
1	5/16/84	1.411	0.928	34.2	27.65	44.85	--	2 kg/hr
2	5/17/84	3.666	0.253	93.1	31.97	42.27	--	precoat
3	5/17/84	3.848	0.368	90.4	19.44	25.29	--	2 kg/hr
4	5/17/84	4.148	0.310	92.5	30.66	23.00	25.0	precoat
5	5/18/84	2.537	0.148	94.2	21.75	10.77	50.5	precoat
6	5/18/84	1.557	0.244	84.3	22.71	22.57	0.1	precoat
7	5/18/84	2.511	0.268	89.3	31.38	38.59	--	precoat
8	5/21/84	3.732	0.940	74.8	25.33	12.87	49.2	5.4 kg/hr
9	5/23/84	2.303	0.230	90.0	23.49	23.20	1.2	precoat
10	5/23/84	5.109	0.084	98.4	19.13	19.21	--	precoat

TABLE 14. SCRUBBER INLET SUMMARY OF TEST RESULTS

Run Code	Moisture (%)	Orsat Analysis (%)		Exhaust Flow Rate (scfm)	Stack Temp. (°F)	Isokinetic (%)	Concentration (gr/scf)		Emission Rate (lb/hr)	
		CO_2	O_2				Particulate	Chloride	Particulate	Chloride
VI-16-01	4.52	6.8	12.1	765.9	742	99.7	0.215	4.21	1.411	27.65
VI-17-02	16.76	7.0	12.0	622.9	836	116.0	0.687	5.99	3.666	31.97
VI-17-03	20.77	7.0	11.7	527.0	865	118.2	0.852	4.30	3.848	19.44
VI-17-04	20.87	6.7	12.1	489.4	845	114.6	0.989	7.31	4.148	30.66
VI-18-05	23.91	6.5	11.8	421.4	759	105.6	0.702	6.02	2.537	21.76
VI-18-06	19.50	6.9	13.1	363.0	694	95.4	0.501	7.30	1.557	22.71
VI-18-07	20.20	7.5	12.4	403.7	703	94.6	0.726	9.07	2.511	31.38
VI-21-08	24.59	6.0	12.5	434.2	649	100.4	1.000	6.81	3.732	25.33
VI-23-09	13.43	4.0	15.5	577.5	720	93.3	0.465	4.75	2.302	23.49
VI-23-10	13.99	3.9	15.3	673.9	688	88.7	0.885	3.31	5.109	19.13

TABLE 15. SCRUBBER OUTLET SUMMARY OF TEST RESULTS

Run Code	Moisture (%)	Orsat Analysis (%)		Exhaust Flow Rate (scfm)	Stack Temp. (°F)	Isokinetic (%)	Concentration (gr/scf)		Emission Rate (lb/hr)	
		CO_2	O_2				Particulate	Chloride	Particulate	Chloride
VO-16-01	3.90	2.5	17.4	1724.2	358	96.4	0.063	3.04	0.928	44.85
VO-17-02	9.21	3.2	16.6	1487.0	359	105.0	0.020	3.32	0.253	42.27
VO-17-03	9.92	2.9	16.9	1484.5	310	105.6	0.029	1.99	0.368	25.29
VO-17-04	8.58	2.7	17.2	1461.9	321	94.0	0.025	1.84	0.310	23.00
VO-18-05	10.03	2.9	15.9	1030.6	288	100.3	0.017	1.22	0.148	10.77
VO-18-06	8.62	3.0	17.0	1283.2	295	87.3	0.022	2.05	0.244	22.57
VO-18-07	8.62	3.0	17.0	1227.7	267	89.0	0.026	3.67	0.268	38.59
VO-21-08	10.72	3.0	15.9	1218.2	289	69.2	0.090	1.23	0.940	12.87
VO-23-09	5.59	2.2	17.8	1272.4	342	104.3	0.021	2.13	0.230	23.20
VO-23-10	7.72	2.0	17.0	1216.4	308	97.2	0.081	1.84	0.084	19.21

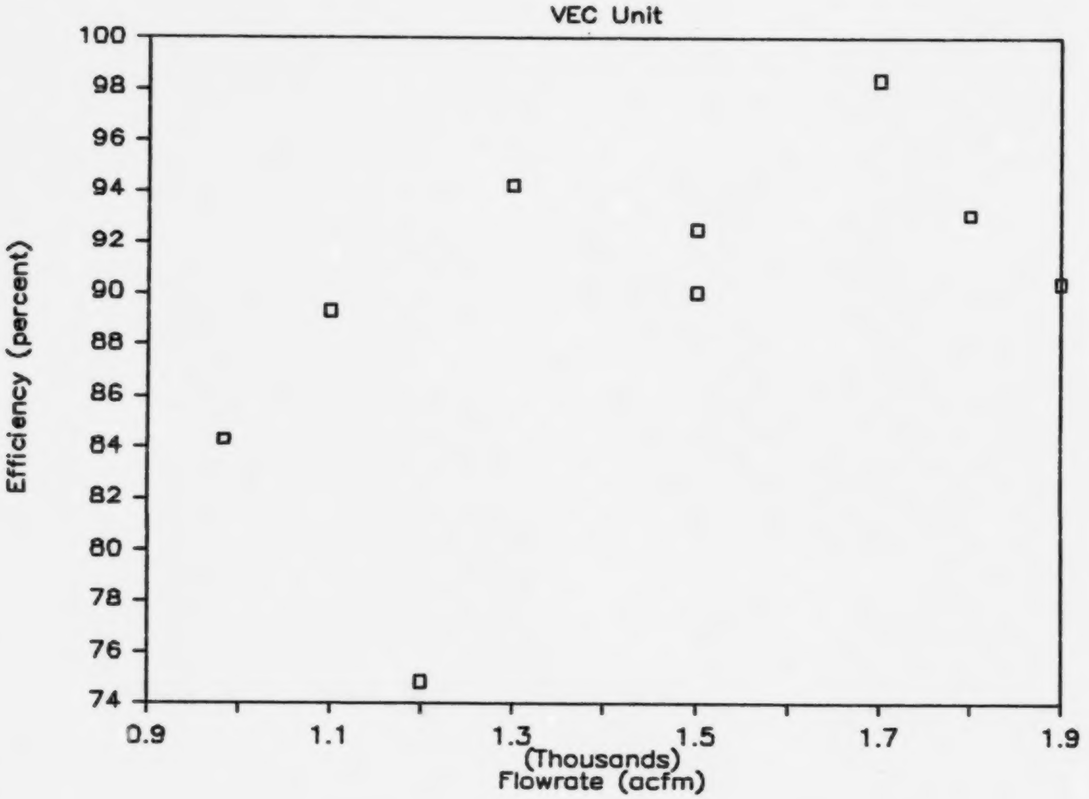

Figure 14. Relationship of total mass removal efficiency and system flow rate: Vulcan unit.

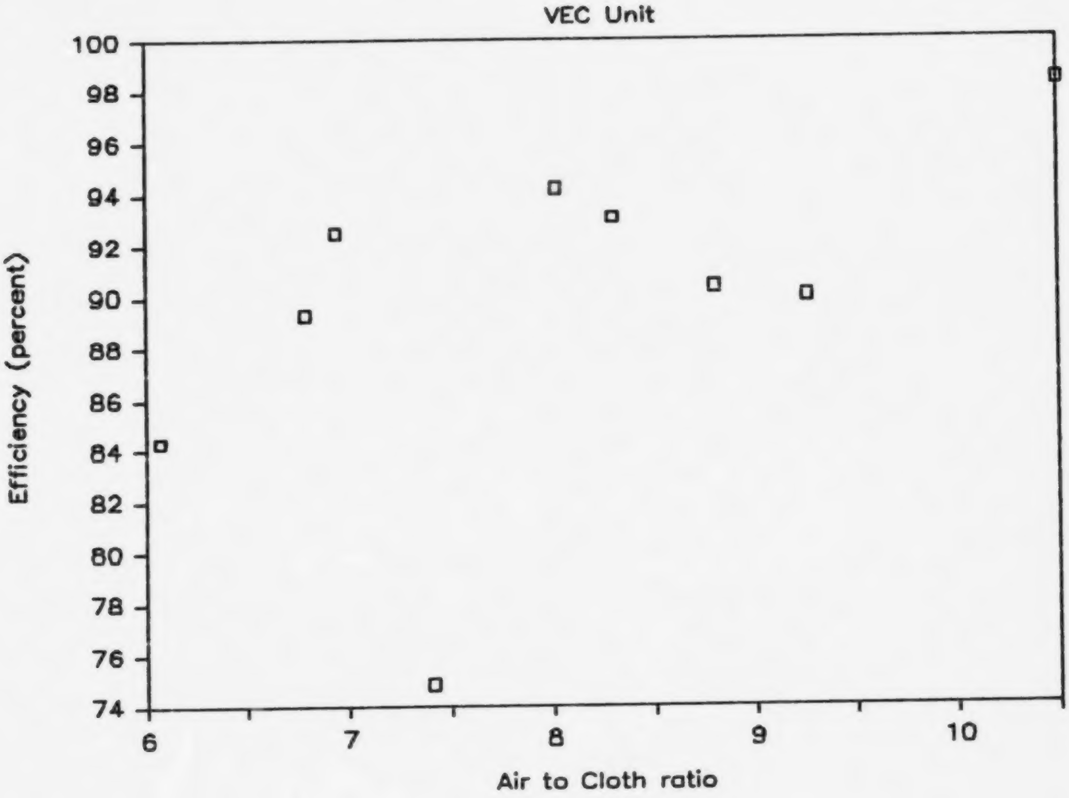

Figure 15. Relationship of total mass removal efficiency and air-to-cloth ratio: Vulcan unit.

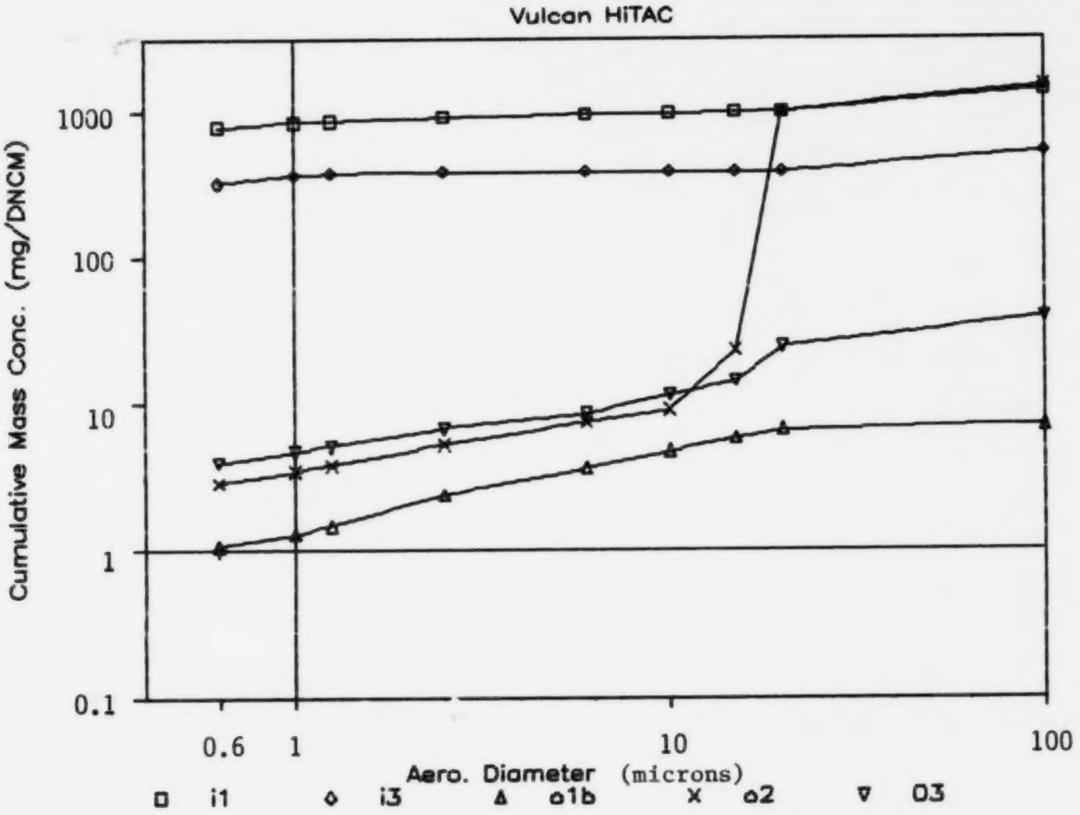

Figure 16. Cumulative mass concentration vs. particle size: Vulcan unit.

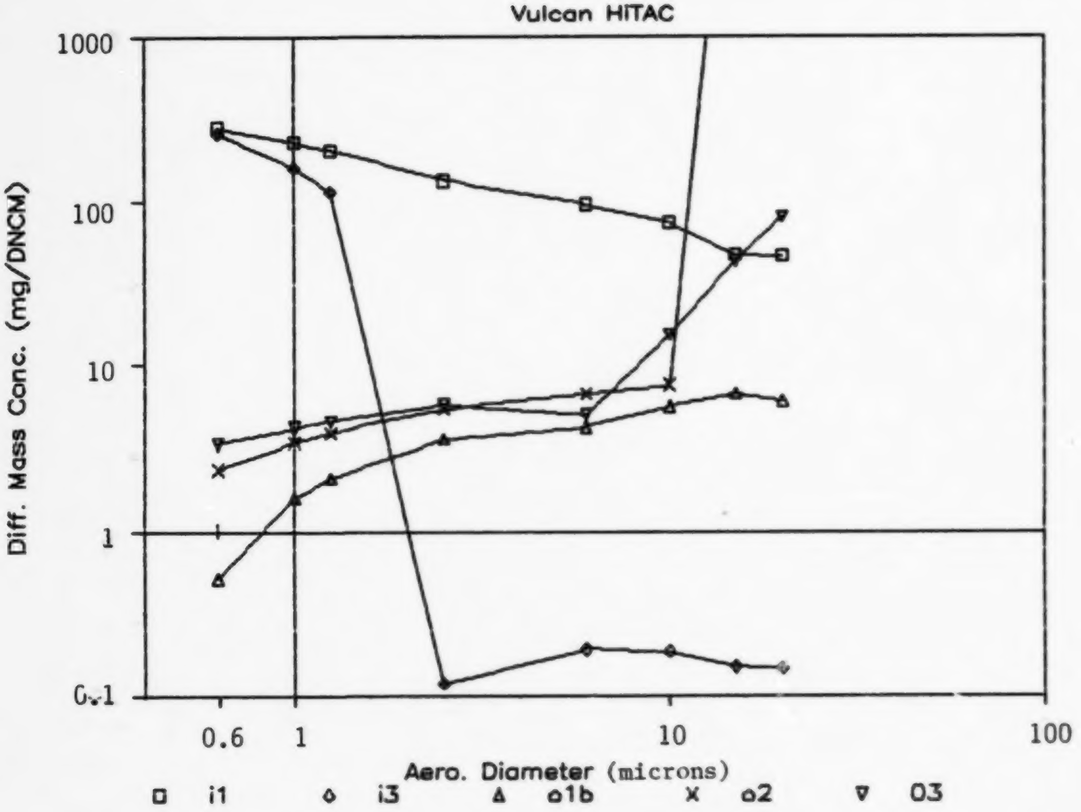

Figure 17. Differential mass concentration vs. particle size: Vulcan unit.

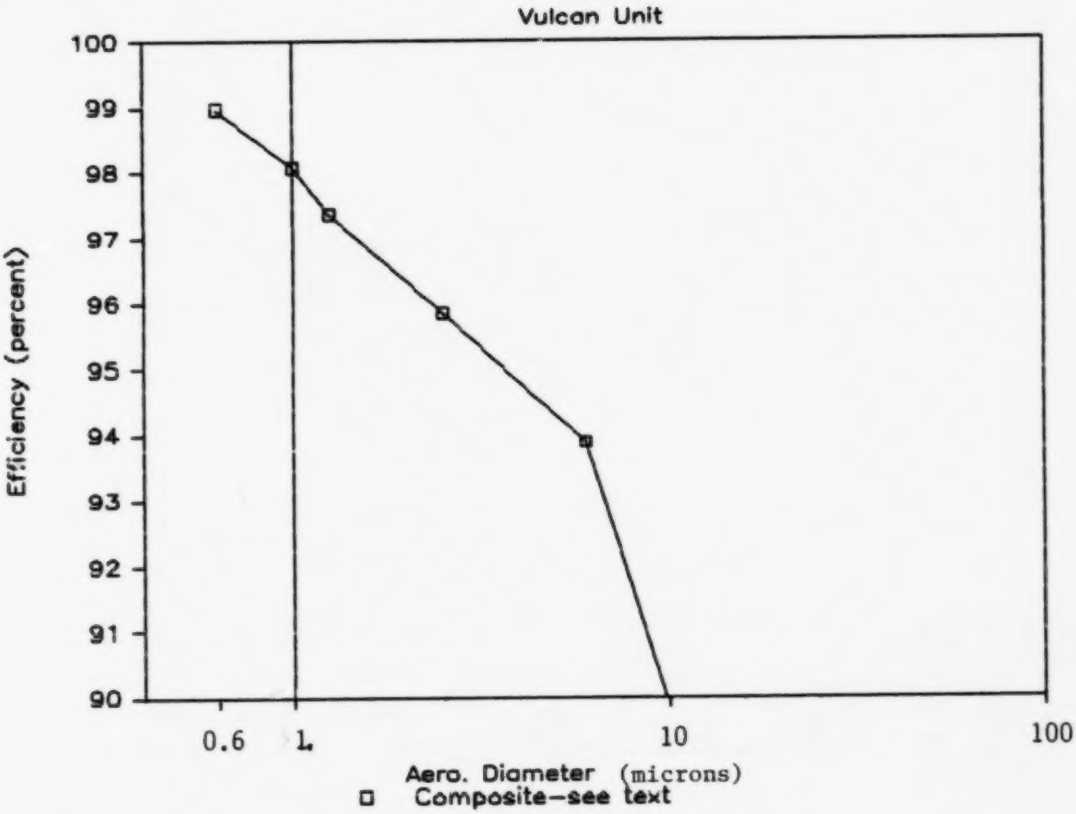

Figure 18. Efficiency of particulate matter removal vs. particle size: Vulcan unit.

These apparently strange results may be due to the method described above for construction of the plots, or determining small differences between highly variable numbers, or to agglomeration of fine, sticky particles passing through the filters.

In summary, the test results indicate that effective control of the fine particulates generated by hazardous waste combustion may be achievable by the Hi-Tac unit. Additional development work to address the problem of sticky particulate will be required.

CONCLUSIONS

1. The Vulcan Hi-Tac unit as currently configured cannot achieve acceptable removal of HCl from incineration of chlorinated hazardous wastes.
2. Particulate removal is erratic on this emission source varying from 32 percent to over 98 percent.
3. The sticky nature of the particulate caused severe problems with filter cleaning.
4. Additional development work is required before this unit can be used to control emissions from incineration of chlorinated hazardous wastes.

SECTION 7

CEILCOTE IWS® SYSTEM

GENERAL DESCRIPTION

The ionizing wet scrubber (IWS®) was developed by the Ceilcote Company for removal of fine particulate matter at low energy levels and high collection efficiencies. The first commercial installation commenced operation in 1972. The system has been installed on over 15 private and municipal waste incinerators handling a variety of wastes. The unit has been used for a number of other applications, including refractory manufacturing, calciners, and fiberglass insulation manufacturing. The scrubber can control both acid gases and particulate matter.

The basis theory of operation of the unit is shown schematically in Figure 19. The incoming polluted gas stream passes through a high voltage ionizing section which imparts on electric charge to the particulate matter. As the charged particles move through the scrubber, they are electrostatically attracted to the surface of the packing material or to a liquid droplet and are thus captured. The captured particles are removed from the system by a continuous cross flow of scrubbing liquid. More detail on the function of individual components of the system (see Figure 20) is contained in the following paragraphs.

The gas stream entering the system first passes through a quencher. Gas temperatures are reduced to about 90 to 95°C (180 to 200°F). The gases then pass through a prescrubber. In the prescrubber, the gas is fully saturated with water vapor and the coarse particulates (i.e., >5 microns) are removed. The prescrubber also serves to generate the particulate which forms due to condensation or gas phase reaction and also to remove entrained liquids.

The saturated gas stream then passes into the ionizer. This high intensity charging section utilizes direct current. The discharge electrode wires are negative polarity. Wetted plates act as grounded electrodes. The wetted plates are continuously irrigated to prevent particle accumulation. Corona discharge from the electrodes produces a gaseous ion emission which attached to the particulate and conveys an electrostatic charge.

The charged particles then enter the scrubber where collection occurs. The packed bed scrubber is a conventional Tellerett packed cross flow wet scrubber. Large particles (>5 microns) not previously removed are collected by inertial impaction on the packing or water droplets produced by the packing/water interactions. The submicron particles are collected by image force attraction. Continuous flow of water over the packing flushes away the collected particles. The gas is then demisted and exhausted to the atmosphere.

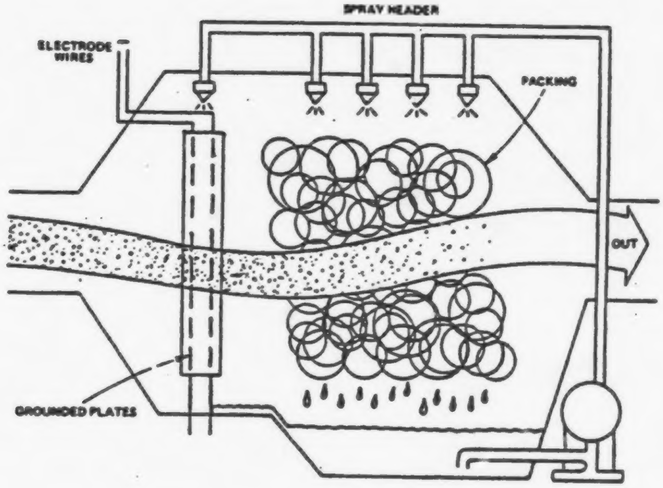
SPRAY HEADER
ELECTRODE WIRES
PACKING
OUT
GROUNDED PLATES

Figure 19. Ceilcote ionizing wet scrubber.

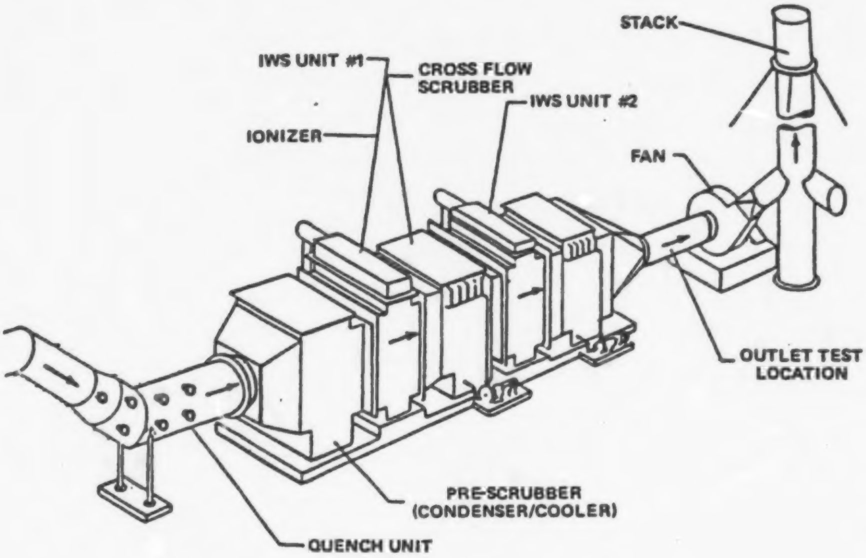
STACK
IWS UNIT #1
CROSS FLOW SCRUBBER
IWS UNIT #2
IONIZER
FAN
OUTLET TEST LOCATION
PRE-SCRUBBER (CONDENSER/COOLER)
QUENCH UNIT

Figure 20. Ceilcote system.

Image force attraction requires some explanation. A charged particle close to a neutral surface will induce an electrostatic charge of opposite polarity on that surface and will then be attracted to it. The force of attraction is equal to the force which would exist between a charged particle and an imaginary particle of equal but opposite polarity located at an equal distance behind the surface. The packing and scrubbing liquid are maintained electrically neutral to create the proper conditions for image force attraction.

The functional capabilities and design flexibility of the IWS system make it ideally suited for control of emissions from hazardous waste incineration. Particles of almost any size or composition can be effectively collected. The Tellerette packing section provides effective capture of the acid gases. Reagents can be added to enhance absorption.

The IWS® is a fractional collector (removal is a percentage of incoming load). Thus additional stages can be added to improve overall collection. For a two-stage system which, say for example, achieves an 80 percent reduction in particulate in the first stage, 80 percent reduction of the remaining 20 percent is collected in the second stage. This would yield an overall efficiency of 96 percent. A third-stage would improve the overall collection efficiency to over 99 percent.

TEST RESULTS

The Ceilcote Company provided a two-stage IWS® for these tests. The unit was shipped to the ENSCO facility in June, 1984, and installed in the test locations. During shakedown operation of the pilot unit, which is constructed principally of FRP plastic, the unit was severely damaged by fire. It is possible the unit's electrical connections were damaged during transport. In any event, the damage was too extensive to allow continuation of the test. We are disappointed at the loss of this unit to the project. We believe that this system shows great applicability to the problem of controlling the fine particulate emissions and acid gases which result from incineration of hazardous wastes.

SECTION 8

QUALITY ASSURANCE

A quality assurance (QA) project plan for the sampling and analysis work performed in this project was approved by EPA prior to commencement of these activities. This plan detailed the type of tests to be conducted, the sampling procedures, analytical procedures, and data reduction methodology. Copies of this document were provided to appropriate project personnel for ready reference prior to and during these activities. Selection of a host incineration facility that would be representative of commercial hazardous waste incineration facilities and air pollution control devices that might be readily obtained as full-scale production units in the near future were important considerations in the planning stages of the project. Development of the engineering plans, the details of the test site development, selection of suitable control devices, sampling and analysis plans, and data evaluation were all considered in developing the QA plan.

An important consideration in the test program was the proper way to obtain a slipstream of incineration exhaust. The objective of this study was to determine the HCl and particulate control capabilities of APCDs with particular emphasis on the fine particulates which are most difficult to control. The location of the slipstream port into the incineration system is in the emergency bypass stack located just upstream from the regular scrubber system. The gas composition of the sampled stream will be representative. Since the large particles (>5 microns) are readily controlled by almost any available pollution control system, extraction of the slipstream gas at right angles to the normal gas flow will produce a not-undesirable bias in particle size distribution toward the ultrafines. These are the more difficult to control, yet are more significant to health-related issues.

Independent quality assurance checks during testing of each APCD were used to assess and enhance the quality of the data. The chloride analysis was checked before analysis of any batch of samples using a solution supplied by the project Quality Assurance Officer. An aliquot of the audit sample was added to the Method 5 impinger. The analyst recovered and analyzed the sample using the same techniques as for sampling runs. The data were back-calculated to determine the chloride concentration in the aliquot supplied. The QA plan specified tolerance of 10 percent was met at each check (see Table 16). While the audit solution was a simple salt in deionized water and thus did not contain possible matrix interferents, it provided assurance that the chloride-specific ion electrode was operating properly. In audit situations, RTI uses EPA-approved checklists to qualitatively evaluate Method 5 and cascade impactor sampling. The sampling for this project was done satisfactorily according to these criteria.

Data for particulate matter measurements is notoriously susceptible to errors from several sources (weighings, flow measurements, etc.). This is especially true of cascade impactor measurements. Table 17 shows comparison of outlet runs for Method 5 and the matched impactor run. Corresponding matching of inlet runs is not valid, due to the wide differences in sampling times and the fluctuations on the source pollutant concentrations.

SECTION 9

CONCLUSIONS

1. All versions of the Hydro-Sonic units tested achieved excellent HCl control. Ninety-nine percent of HCl was obtained without adding additional alkalinity to the ENSCO scrubber recycle water. With additional alkalinity, any of these units should be capable of well over 99 percent HCl removal.

2. The Tandem Nozzle SuperSub Model 100 achieved the best particulate removal of the three Hydro-Sonic units tested.

3. The ETS dry scrubber achieved both high removal efficiencies for HCl and particulate.

4. The ETS scrubber reagent consumption, hydrated lime, appears to be high (3 moles lime per mole HCl) but cannot be stated with confidence since no attempts were made to improve utilization through reagent recycle.

5. The ETS unit does not presently have capability to adjust reagent feed rate to accommodate rapidly varying HCl content in the gas to be treated.

6. The Vulcan Hi-Tac unit is not designed to, and cannot presently, remove acid gases from the exhaust gas being treated. Therefore, it is not applicable to incinerators burning significant amounts of halogenated hazardous wastes.

7. Further development work and/or emissions testing will be required before the Hi-Tac unit demonstrates the capability to reliably control sources which might produce sticky particulate as encountered in the exhaust of the ENSCO incinerator.

8. Considerable variability was encountered in the ENSCO exhaust gas for particulate concentration, particulate size distribution, HCl concentration, flue gas moisture content, and exhaust gas temperature. It is necessary that any air pollution control device installed on a hazardous waste incinerator have design features that allow compensation for this variability.

9. Of the APCDs tested in this project, the Hydro-Sonic Tandem Nozzle SuperSub gave the best overall performance in terms of HCl and particulate removal and ability to accommodate variability in the gas stream being treated.

REFERENCES

1. Tatsch, C.W., W.M. Yeager, and G.L. Johnson, 1984. PADRE: A computerized data reduction system for cascade impactor measurements. Journal of the Air Pollution Control Association, Volume 34, No. 6, pp. 655-660.

APPENDIX: SITE TEST REPORTS

HYDRO-SONIC GAS CLEANER
DEMONSTRATION TESTS
ON A HAZARDOUS WASTE INCINERATOR
MARCH 15-23, 1984

Prepared For
Research Triangle Institute
Research Triangle Park, N.C.
(RTI PO #43724, Gov. Contract #68-03-3149)

By
Hydro-Sonic Systems
Affiliate of Lone Star Steel
P. O. Box 97
Lone Star, Texas 75668

May 25, 1984

HYDRO-SONIC GAS CLEANER
DEMONSTRATION TESTS
ON A HAZARDOUS WASTE INCINERATOR

I. INTRODUCTION

Tests were made to demonstrate the cleaning capabilities of the Lone Star Steel Company Hydro-Sonic cleaners when attached to the off-gas of the Ensco hazardous waste incinerator at El Dorado, Arkansas. The Model 100 Steam-Hydro, Model 100 Tandem Nozzle Hydro, and Model 100 SuperSub Tandem Nozzle Hydro were all tested from March 15 thru 23, 1984.

II. SUMMARY

The gas cleaning for most of the tests exceeded the cleaning requirements of .08 grains per standard cubic foot corrected to 12 percent CO_2 at the inlet. The best cleaning was achieved with the Tandem Nozzle SuperSub Hydro with fresh water injection.

Run 104 (Test 4 for sampling) gas sampling results were invalid and will be omitted in the final exit grain loading.

The following parameters were applicable to the cleaners tested:

1. Steam-Hydro

Steam used, pound per pound of inlet gas	.144 to .191
Steam pressure in psig	92 to 98
Injection water at steam nozzle exit, pounds per pound of inlet gas	.877 to 1.073
Cooling water, pounds per pound of inlet gas	.578 to .855
Prequench water, pounds per pound of inlet gas	.203 to .244

2. Tandem Nozzle

Pressure across cleaning unit in inches of water gage	32.5 to 35.0
Injection water for cooling gas, pounds per pound of inlet gas	.813 to 1.829
Injection water at the first nozzle exit, pounds per pound of inlet gas	1.007 to 1.426
Injection water at the second nozzle exit, pounds per pound of inlet gas.	.733 to 1.298

3. Tandem Nozzle SuperSub

Steam used in steam nozzle, pounds per pound of inlet gas	.039 to .041
Injection water at steam nozzle exit, pounds per pound of inlet gas	.173 to .218
Steam pressure in psig	110
Pressure across cleaning unit in inches of water gage	31.2 to 34.4
Injection water for cooling pounds per pound of inlet gas	.562 to .826
Injection water at the first nozzle exit, pounds per pound of inlet gas	.891 to 1.364
Injection water at the second nozzle exit, pounds per pound of inlet gas	1.229 to 1.293

III. DISCUSSION

The physical arrangements for testing the Steam-Hydro are shown in Figure 1. The inlet sampling was conducted just upstream of the inlet gas venturi. The dry-bottom quench was part of Ensco's piping and was not instrumented. Figure 2 shows the physical setup for the Tandem Nozzle and the Tandem Nozzle SuperSub. The inlet sampling was conducted upstream of the quench and the moisture at the venturi had to be calculated from a heat balance. Again the dry-bottom quench was part of Ensco's piping and was not instrumented.

IV. CONCLUSION

The best gas cleaning occurred during the Tandem Nozzle SuperSub test with fresh water injection. Most of the gas cleaning for all of the tests exceeded the standard of .08 grains per standard cubic foot with 12 percent CO_2 in the inlet gas stream.

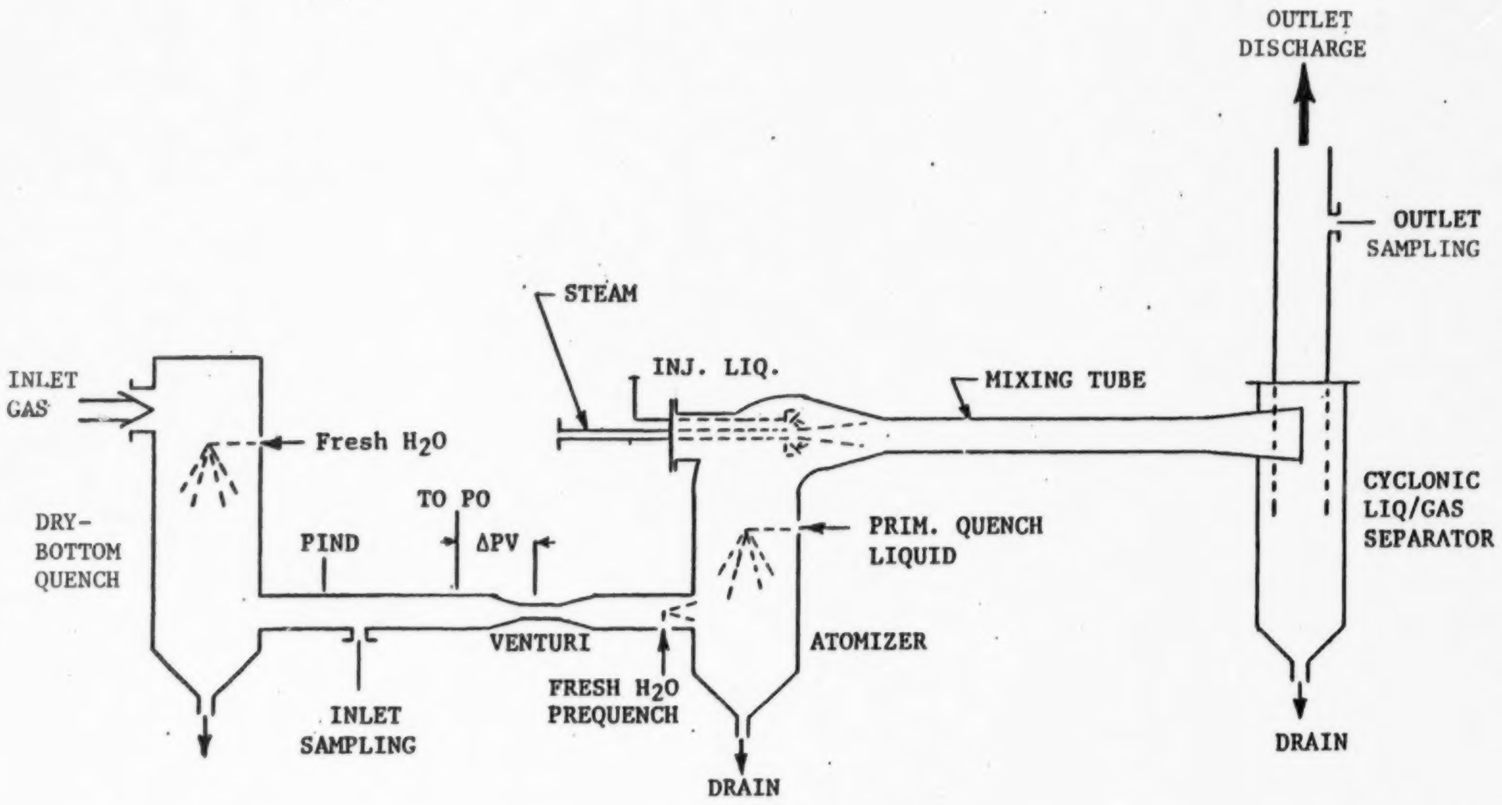
OUTLET DISCHARGE
OUTLET SAMPLING
STEAM
INJ. LIQ.
MIXING TUBE
INLET GAS
Fresh H_2O
TO PO
DRY-BOTTOM QUENCH
PIND
ΔPV
PRIM. QUENCH LIQUID
CYCLONIC LIQ/GAS SEPARATOR
VENTURI
ATOMIZER
FRESH H_2O PREQUENCH
INLET SAMPLING
DRAIN
DRAIN

FIGURE 1. STEAM HYDRO TEST CONFIGURATION (ENSCO/MARCH 1984)

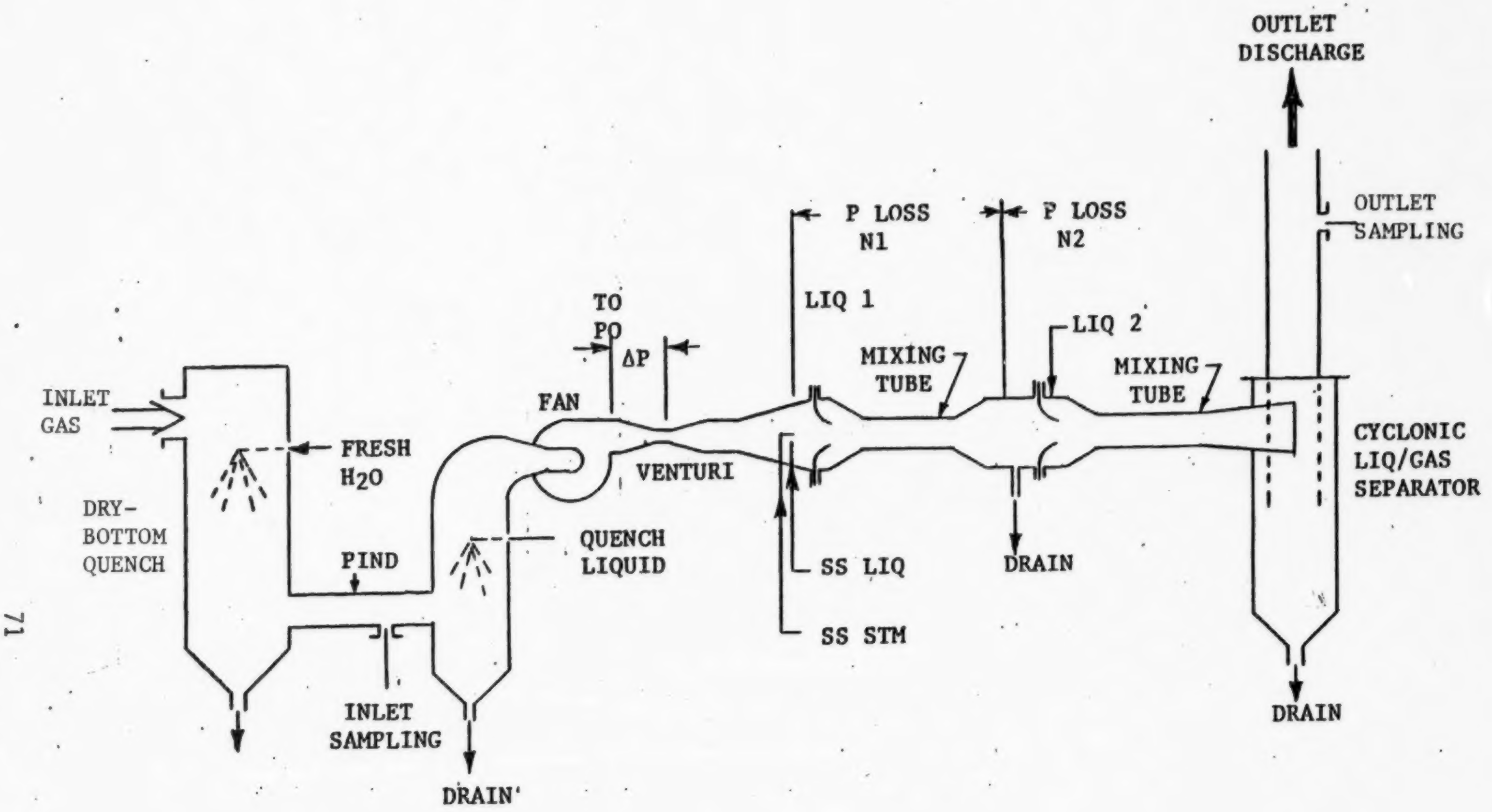
OUTLET DISCHARGE
OUTLET SAMPLING
CYCLONIC LIQ/GAS SEPARATOR
DRAIN
P LOSS N1
P LOSS N2
LIQ 1
LIQ 2
MIXING TUBE
MIXING TUBE
DRAIN
SS LIQ
SS STM
TO
PO
ΔP
FAN
VENTURI
QUENCH LIQUID
INLET GAS
FRESH H2O
DRY-BOTTOM QUENCH
PIND
INLET SAMPLING
DRAIN'

FIGURE 2. TANDEM NOZZLE & SUPERSUB TEST CONFIGURATION (ENSCO/MARCH 1984)

APPENDIX A

STEAM-HYDRO

STEAM-HYDRO

DATA NOMENCLATURE

Run	Hydro-Sonic test number
Date	Date test was made.
Time	Time test was started in 24-hour time.
ΔPV	Differential pressure across inlet gas venturi, inches of water gage.
PAD	Static pressure upstream of the inlet gas venturi, inches of water gage.
PTS	Static pressure at inlet of unit in front of the steam nozzle, inches of water gage.
PMIS	Static pressure at inlet of mixing tube, inches of water gage.
PIND	Static pressure in the inlet duct ahead of the inlet gas venturi, inches of water gage.
PCS	Static pressure at inlet to the cyclonic liquid/gas separator, inches of water gage.
PCOS	Static pressure in the exit stack of the cyclonic liquid/gas separator, inches of water gage.
PINJ	Water pressure at inlet of the water injection ring surrounding the exit of the supersonic steam nozzle in psig.
PBAR	Barometric pressure, inches of mercury absolute.
PST	Steam pressure at inlet of the supersonic steam nozzle in psig.
TAD	Static temperature at inlet of the inlet gas venturi, degrees Fahrenheit.
TAT	Static temperature at inlet of atomizer in degrees Fahrenheit.
TCO	Static temperature at exit of cyclonic separator, degrees Fahrenheit.
TAW	Injection water temperature to atomizer, degrees Fahrenheit.
PMOS	Static pressure at exit of mixing tube, inches of water gage.

STEAM-HYDRO DATA NOMENCLATURE (CONTINUED)

TINJ	Injection water temperature to the water injection ring surrounding the exit of the supersonic steam nozzle, degrees Fahrenheit.
TCW	Temperature of water entering the prequench water nozzle ahead of the atomizer, degrees Fahrenheit.
TST	Steam temperature at inlet to the steam supersonic nozzle, degrees Fahrenheit.
QAW	Water flow through the atomizing water nozzle, gpm.
QINJ	Water flow through the nozzles in the water injection ring surrounding the steam supersonic nozzle exit, gpm.
QCW	Water flow through the prequench nozzle, gpm.
DN	Throat diameter of the supersonic steam nozzle, inches.
INJ. NOZ	Number and type of water injection nozzles in the water injection ring surrounding the exit of the supersonic steam nozzle.

Pg 1 of 2

R & D DATA SHEET

Date

Location ENSCO, ELDORADO, ARK Model 100 STEAM HYDRO

WHOLE NO. DECIMAL RUN	101	102	103	104	105	106	REMARKS
DATE	3/15/84	3/15/84	3/16/84	3/16/84	3/17/84	3/17/84	
TIME	1308	1745	0902	1245	1225	1500	
3-2 ΔPV	1.865	1.875	1.895	1.89	1.918	1.88	
±3-1 PAD	-7.5	-7.3	-7.9	-3.48	-5.6	-5.94	
±3-1 PTS	-8.4	-7.9	-8.8	-4.4	-6.3	-6.5	
±3-1 PMIS	-9.0	-8.6	-9.7	-4.9	-7.0	-7.2	
±3-1 PMOS	1.5	1.47	1.5	1.36	1.0	1.0	
±3-1 PIND	-3.3	-3.2	-3.3	-3.0	-3.1	-3.3	
±3-1 PCS	1.5	1.47	1.5	1.34	1.0	1	
±3-1 PCOS	.1	.1	.1	.1	.1	.1	
3-0 PINJ	45	45	45	46	28	33	
2-2 PBAR	29.76	29.73	29.85	29.812	29.712	29.668	
3-0 PST	98	98	98	92	92	92	
3-0 TAD	440	450	470	471	464	479	
3-0 TAT	167	165	168	165	162	153	
3-0 TCO	177	176	179	172	165	161	
3-0 TAW	70	70	70	70	69.6	70	
3-0 TINJ	170	170	170	172	69.6	70	
3-0 TCW	70	70	70	70	69.6	78	
3-0 TST	332	332	334	328	327	328	
3-2 QAW GPM	5	5	5	5	6.5	7.3	
3-2 QINJ GPM	9	9	9	9	7.59	8.79	
3-2 QCW GPM	1.875	2.05	2	2.05	1.96	2.05	
DN	4.33	4.33	4.33	.388	.388	.388	
INJ. NOZ.	6V15	6V15	6V15	6V15	6V15	6V15	

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Pg 2 of 2 12

R & D DATA SHEET

Date

Location ENSCO, ELDORADO, ARK Model 100 STEAM-HYDRO

WHOLE NO. DECIMAL							REMARKS
RUN	107	108	109				
DATE	3/19/84	3/19/84	3/19/84				—
TIME	0830	1250	1530				
3-2 ΔPV	1.866	1.8	1.682				
±3-1 PAD	-5.92	-4.83	-4.83				
±3-1 PTS	-6.5	-5.6	-5.6				
±3-1 PMIS	-7.2	-6.0	-6.0				
±3-1 PMOS	1.0	1.2	1.2				
±3-1 PIND	-3.3	-3.1	-3.1				
±3-1 PCS	1.0	1.2	1.2				
±3-1 PCOS	.1	.1	.1				
3-0 PINJ	34.6	57	55.7				
2-2 PBAR	29.438	29.45	29.45				
3-0 PST	92	92	92				
3-0 TAD	469	438	441				
3-0 TAT	156	157	157				
3-0 TCO	164	172	166				
3-0 TAW	68	69.7	69.7				
3-0 TINJ	68	69.7	165.7				
3-0 TCW	68	69.7	69.7				
3-0 TST	328	330	330				
3-2 QAW GPM	7	7	7				
3-2 QINJ GPM	9	9	9				
3-2 QCW GPM	2.05	2	2				
DN	.388	.388	.388				
INJ. NOZ	6V15	6V15	6V15				

STEAM-HYDRO

NOTES ON METHODS OF CALCULATION

1. The inlet gas moisture in percent by volume was taken from the inlet gas sampling data.

2. The mol fractions of the inlet gas constitutes were taken from the inlet gas sampling data.

3. The gas constant used in the calculations was 1545.325.

4. Conversion factors for pressures were as follows:

   .49116 pounds per square inch per inch of mercury

   .03605 pounds per square inch per inch of water

5. The inlet gas venturi used to measure gas flow had a throat diameter of 6.138 inches and an upstream diameter of 8.316 inches.

6. The inlet gas venturi and the supersonic steam nozzles were stainless steel and a coefficient of temperature expansion of .0000092 inch/inch/degree Fahrenheit was used in the calculations.

7. A conversion factor of 459.699 was used to convert degrees Fahrenheit to degrees Rankine.

8. Dry gas compositions by volume and weight.

	Volume Fraction			Molecular Weight	Weight Fraction		
Run	CO_2	O_2	N_2	Dry Gas	CO_2	O_2	N_2
101	.07	.11	.82	29.57389	.1042	.1190	.7768
102	.069	.123	.808	29.60969	.1026	.1329	.7645
103	.063	.116	.821	29.48583	.0940	.1259	.7801
104	.066	.126	.808	29.57365	.0982	.1363	.7655
105	.062	.127	.811	29.51366	.0925	.1377	.7698
106	.067	.124	.809	29.58168	.0997	.1341	.7662
107	.068	.116	.816	29.5658	.1012	.1256	.7732
108	.055	.137	.808	29.44153	.0822	.1489	.7689
109	.066	.12	.814	29.54975	.0983	.13	.7717

9. Moisture contents of inlet gas:

Run	Moisture by Volume	Moisture by Weight
101	.26	.21404
102	.227	.178678
103	.281	.23879
104	.212	.163894
105	.267	.222353
106	.245	.197631
107	.266	.22083
108	.231	.183816
109	.258	.211992

10. Run numbers identified with sampling tests:

Run	Sampling Test No.
101	1
102	2
103	3
104	4
105	5
106	6
107	7
108	8
109	9

STEAM-HYDRO

METHODS OF CALCULATION

1. All pressures measured in inches of water gage, except the differential pressures, were converted to absolute pressures by the following:

   PX = PBAR × .49116 + PXG × .03605

   PXG = Pressure in inches of water gage

2. The weight of moisture in the gas stream at the inlet venturi, WVV, in pounds of water vapor per pound of dry gas, was equal to the weight of moisture from (9) of the Notes on Methods of Calculations.

3. The weight of gas at the inlet gas venturi, WGV, in pounds per minute was calculated as follows:

$$WGV = \frac{Cd \times Fa \times \pi \times D^2 \times 60}{4 \times 144} \sqrt{\frac{2 \times g \times 144 \times \frac{\gamma}{(\gamma - 1)} \times \frac{P_1}{\rho_1} \times \left[1 - \left(\frac{P_2}{P_1}\right)^{\frac{\gamma - 1}{\gamma}}\right]}{\left[1 - \left(\frac{P_2}{P_1}\right)^{\frac{2}{\gamma}} \times \beta^4\right]}}$$

   Cd = .985 flow coefficient

$$Fa = \left[\frac{(1 + TAD \times .0000092)}{(1 + 70 \times .0000092)}\right]^2$$

   g = 32.174 ft/sec^2

   D = 6.138 diameter in inches of venturi throat

   $\gamma = \gamma GV = (\gamma DG + WVV \times \gamma H_2O)/(1 + WVV)$

   WVV from (2) above

$\gamma DG = \chi CO_2 \times \gamma CO_2 + \chi O_2 \times \gamma O_2 + \chi N_2 \times \gamma N_2$

χCO_2 = weight fraction CO_2 in dry gas

γCO_2 = gamma of CO_2 @ TAD

χO_2 = weight fraction of O_2 in dry gas

γO_2 = gamma of O_2 @ TAD

χN_2 = weight fraction of N_2 in dry gas

γN_2 = gamma of N_2 @ TAD

γH_2O = gamma of water vapor @ TAD

P_1 = PAD in psia

P_2 = PAD − ΔPV × .03605

β = 6.138/8.316 from (5) of Notes on Methods of Calculations

$\rho = \rho GV = PAD \times 144/[RG \times (459.688 + TAD)]$

$$RG = \frac{RDG + RV \times WVV}{(1 + WVV)}$$

RDG = 1545.325 ÷ MWDG

MWDG = molecular weight of dry gas from (8) Notes on Methods of Calculation.

$$RV = \frac{PAD \times VV \times 144}{(459.688 + TAD)}$$

VV = Specific volume of water vapor at PAD and TAD.

4. The weight of dry gas at the inlet gas venturi, WDGV, in pounds per minute was calculated as follows:

WDGV = WGV/(1 + WVV)

WGV from (3) above.

WVV from (2) above.

5. The volume of gas flow at the inlet gas venturi, QCV, in actual cubic feet per minute was calculated as follows:

$QGV = WGV/\rho GV$

WGV from (3) above.

ρGV from (3) above.

6. The volume of dry gas at the inlet gas venturi, QDGV, in standard dry cubic feet per minute was calculated as follows:

$QDGV = WDGV/\rho STD$

WDGV from (4) above.

ρSTD = specific weight of dry gas at 14.696 psia and 68°F

$$= \frac{14.696 \times 144 \times MWDG}{1545.325 \times 527.688}$$

7. The specific weight of gas at the inlet gas venturi, ρGV, in pounds per cubic foot, was calculated in (3) above.

8. The ratio of the specific heats of the gas at the inlet gas venturi, γGV, was calculated in (3) above.

9. The weight of the cooling prequench water, WCW, in pounds per minute, was calculated as follows:

$WCW = QCW \times DCW$

DCW = density of water in pounds per gallon @ TCW

10. The weight of quenching atomizer water, WAW, in pounds per minute, was calculated as follows:

$WAW = QAW \times DAW$

DAW = density of water in pounds per gallon at TAW

11. The weight of injection water at the steam nozzle exit, WINJ, in pounds per minute, was calculated as follows:

$WINJ = QINJ \times DINJ$

DINJ = density of water in pounds per gallon at TINJ

12. The rate of water injected into the prequench nozzle, αCW, in pounds per pound of inlet venturi gas, was calculated as follows:

$\alpha CW = WCW/WGV$

WCW from (9) above.

WGV from (3) above.

13. The rate of water injected through the nozzles in the atomizer, αAW, in pounds per pound of inlet venturi gas was calculated as follows:

$\alpha AW = WAW/WGV$.

WAW from (10) above

WGV from (3) above

14. The rate of water injected through the nozzles in the injection ring on the exit of the supersonic steam nozzle, αINJ, in pounds of water per pound of inlet venturi gas, was calculated as follows:

$\alpha INJ = WINJ/WGV$ WINJ from (11) above. WGV from (3) above.

15. The steam flow through the supersonic steam nozzle, WST, in pounds per minute was calculated at the nozzle throat as follows:

$$WST = \frac{A \times V \times Fa \times 60}{144 \times Vg}$$

A = area of steam nozzle throat = $\frac{\pi}{4} \times DN^2$

$$Fa = \left[\frac{(1 + .0000092 \times TST)}{(1 + .0000092 \times 70)}\right]^2$$

V = velocity of steam ft/sec = $\sqrt{778.3 \times 2g\Delta h}$

778.3 ft lbs = 1 Btu

$g = 32.174$

$\Delta h = (H_1 - H_2) \times \overline{.965}^2$

H_1 = Btu per pound of steam at PSTA dry saturated

H_2 = Btu per lb of steam at quality X2 and throat pressure PTH

$PSTA = PST + PBAR \times .49116$

$PTH = [\gamma/(\gamma + 1)] \times PSTA$

γ = gamma of steam at PSTA dry saturated

$X2 = (S1 - Sf2)/Sfg2$

S1 = entropy of dry saturated steam at PSTA

Sf2 = entropy of the liquid at PTH

Sfg = entropy of evaporation at PTH

$H2 = hf2 + X2 \times hfg2$

hf2 = enthalpy of liquid at PTH

hfg2 = enthalpy of evaporation at PTH

$H2ACT = H1 - \Delta h$

Quality of steam at PTH = $(H2ACT - hf2) \div hfg2 = Xth$

$Vg = Vf + XTH(Vg - Vf)$

Vf = volume of liquid at PTH dry saturated

Vg = volume of steam vapor at PTH dry saturated

16. The steam rate to the Steam-Hydro, αST, pounds per pound of inlet venturi gas, was calculated as follows:

$\alpha ST = WST/WGV$

WST from (15) above.

WGV from (3) above.

17. The total water rate to the Steam-Hydro, αTW, in pounds per pound of inlet gas, was the following sum:

$\alpha TW = \alpha CW + \alpha AW + \alpha INJ + \alpha ST$

αCW from (12) above.

αAW from (13) above.

αINJ from (14) above.

αST from (16) above.

18. The weight of water vapor in the exit gas stream, WVEX, pounds per pound of dry gas, was calculated as follows:

$$WVEX = pv \times 18.016/\left[MDWG \times (PEX - pv)\right]$$

pv = water vapor pressure at TEX

18.016 molecular weight of water vapor

MWDG from (8) of Notes on Methods of Calculation.

$PEX = PCOS \times .03605 + PBAR \times .49116$

$TEX = TCO$

19. The weight of exit gas stream, WGEX, in pounds per minute was calculated as follows:

$$WGEX = (1 + WVEX) \times WDGV$$

WVEX from (18) above.

WDGV from (4) above

20. The specific weight of the gas at the exit, ρGEX, in pounds per cubic foot was calculated as follows:

$$\rho GEX = \frac{PEX \times 144}{RGEX \quad (459.688 + TEX)}$$

PEX from (18) above

TEX from (18) above

$RGEX = (RDG + WVEX \times RVEX)/(1 + WVEX)$

RDG from (3) above

$$RVEX = \frac{VVEX \times PEX \times 144}{(459.688 + TEX)}$$

VVEX = specific volume of water vapor at PEX and TEX

21. The volume of the exit gas, QGEX, in actual cubic feet per minute, was calculated as follows:

$$QGEX = WGEX/\rho GEX$$

WGEX from (19) above

ρGEX from (20) above

ENSCO ELDORADO ARK.

MODEL 100 STEAM-HYDRO

CALCULATED DATA

SHEET 2 OF 2

RUN	101	102	103	104	105	106	107	108
DATE	3/15/84	3/15/84	3/16/84	3/16/84	3/17/84	3/17/84	3/19/84	3/19/84
TIME	1308	1745	0402	1245	1225	1500	0830	1250
ΔPV	1.865	1.875	1.845	1.89	1.918	1.88	1.866	1.8
PAD	14.346	14.340	14.377	14.517	14.392	14.358	14.245	14.294
TAD	440	450	470	471	464	479	469	438
WGV	72.03	72.39	71.35	71.92	72.08	71.14	70.61	71.06
WVV	.21404	.17868	.23879	.16389	.222353	.197631	.22083	.183816
WDGV	59.33	61.42	57.60	61.79	58.97	59.40	57.83	60.02
QGV	1824	1825	1874	1854	1876	1864	1864	1784
QDGV	776	802	751	808	773	777	757	788
ρGV	.03952	.03968	.03807	.03881	.03843	.03812	.03789	.03983
γGV	1.3601	1.3613	1.3587	1.3610	1.3596	1.3589	1.3585	1.3639
QCW	1.875	2.05	2	2.05	1.96	2.05	2.05	2.05
WCW	15.62	16.66	16.66	17.07	14.66	17.07	17.08	16.66
αCW	.217	.230	.233	.237	.203	.240	.242	.234
QAW	5	5	5	5	6.5	7.3	7	7
WAW	41.64	41.64	41.64	41.64	54.14	60.80	58.31	58.31
αAW	.578	.579	.584	.579	.751	.855	.826	.821
QINJ	9	9	9	9	7.59	8.79	9	9
WINJ	73.14	73.14	73.14	73.09	63.21	73.21	74.98	73.28
αINJ	1.015	1.010	1.025	1.016	.877	1.029	1.062	1.031
PSTA	113	113	113	106.6	106.6	106.6	106.6	106.6
TST	332	332	332	328	328	328	328	328
DN	.433	.433	.433	.388	.388	.388	.388	.388
WST	13.732	13.732	13.732	10.372	10.372	10.372	10.372	10.372
αST	.191	.190	.192	.144	.144	.146	.147	.146
αTW	2.001	2.009	2.034	1.976	1.475	2.27	2.277	2.232

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ENSCO ELDORADO ARK.

MODEL 100 STEAM-HYDRO

CALCULATED DATA SHEET 2 OF 2

RUN	101	102	103	104	105	106	107	108
DATE	3/15/84	3/15/84	3/16/84	3/16/84	3/17/84	3/17/84	3/19/84	3/19/84
TIME	1308	1745	0902	1245	1225	1500	0830	1250
PEX	14.62	14.606	14.667	14.646	14.597	14.575	14.462	14.464
TEX	177	176	179	172	165	161	164	172
WVEX	,56101	.54148	.60109	.46407	.34753	.30478	.34008	.46165
WGEX	92.61	94.68	92.22	90.46	78.01	77.50	77.50	87.73
ρGEX	.05197	.0520	.05164	.05354	.05567	.05671	.05542	.05283
QGEX	1782	1814	1786	1690	1401	1367	1399	1661

ENSCO ELDORADO ARK.

MODEL 100 STEAM-HYDRO
CALCULATED DATA

SHEET 1 OF 2

RUN	109							
DATE	3/19/84							
TIME	1530							
ΔPV	1.682							
PAD	14.290							
TAD	441							
WGV	68.30							
WVV	.211992							
WDGV	56.35							
QGV	1736							
QDGV	737							
ρGV	.03934							
γGV	1.3608							
QCW	2							
WCW	16.66							
αCW	.244							
QAW	7							
WAW	58.30							
αAW	.854							
QINJ	9							
WINJ	73.30							
αINJ	1.073							
PSTA	106.6							
TST	330							
DN	.388							
WST	10.372							
αST	.152							
αTW	2.323							

ENSCO ELDORADO ARK.

MODEL 100 STEAM-HYDRO

CALCULATED DATA

SHEET 2 OF 2

RUN	109							
DATE	3/19/84							
TIME	1530							
PEX	14.468							
TEX	166							
WVEX	.34205							
WGEX	75.63							
ρGEX	.05521							
QGEX	1370							

APPENDIX B

TANDEM NOZZLE FAN HYDRO

AND

TANDEM NOZZLE SUPERSUB HYDRO

TANDEM NOZZLE

DATA NOMENCLATURE

Run	Hydro-Sonic Systems Test Number
Date	Month, day, and year of test
Time	Twenty-four hour time of start of the test
ΔPV	Differential pressure across the inlet gas venturi, inches of water gage.
PAD	Static pressure at inlet of the inlet gas venturi, inches of water gage.
PN-1	Static pressure at inlet of the first subsonic gas nozzle, inches of water gage.
ΔPN-1	Differential pressure across the first subsonic gas nozzle, inches of water gage.
PN-2	Static pressure at inlet of the second subsonic gas nozzle, inches of water gage.
ΔPN-2	Differential pressure across the second subsonic gas nozzle, inches of water gage.
PMIS-2	Static pressure at inlet of the second mixing tube, inches of water gage.
PMOS-2	Static pressure at exit of the second mixing tube, inches of water gage.
PCS	Inlet static pressure of the cyclonic liquid/gas separator, inches of water gage.
PCOS	Exit static pressure of the cyclonic liquid/gas separator, inches of water gage.
PINJ-1	Water pressure, PSIG, to the water injection ring surrounding the exit of the first subsonic gas nozzle.
PINJ-2	Water pressure, PSIG, to the water injection ring surrounding the exit of the second subsonic gas nozzle.
PBAR	Barometric pressure, inches of mercury absolute.
TAD	Temperature of the inlet gas of the inlet gas venturi, degrees Fahrenheit

TANDEM NOZZLE DATA NOMENCLATURE (CONTINUED)

TN-1	Temperature of the inlet gas of the first subsonic gas nozzle, degrees Fahrenheit.
TN-2	Temperature of the inlet gas of the second subsonic gas nozzle, degrees Fahrenheit.
TCO	Temperature of the gas at the exit of the cyclonic liquid/gas separator, degrees Fahrenheit.
TCW	Temperature of the cooling water injected into the gas stream in the quench chamber
TINJ	Temperature of water to the water injection rings surrounding the exits of the two subsonic gas nozzles, degrees Fahrenheit.
QCW	Cooling water flow, GPM, to the water injection nozzle in the quench chamber upstream of the fan.
QINJ-1	Water flow, GPM, to the water injection ring surrounding the exit of the first subsonic gas nozzle..
QINJ-2	Water flow, GPM, to the water injection ring surrounding the exit of the second subsonic gas nozzle.
DN-1	Exit diameter, inches, of the first subsonic gas nozzle.
DN-2	Exit diameter, inches, of the second subsonic gas nozzle.
INJ NOZ-1	Number and type of water injection nozzles in the water injection ring surrounding the exit of the first subsonic gas nozzle.
INJ NOZ-2	Number and type of water injection nozzles in the water injection ring surrounding the exit of the second subsonic gas nozzle.

R & D DATA SHEET

PAGE 1 OF 1

OCATION ENSCO, ELDORADO, ARK. MODEL 100 TANDEM NOZZLE HYDRODATE

No Decimal	RUN	110	111	112	116			REMARKS
	DATE	3/20/84	3/21/84	3/21/84	3/22/84			
	TIME	1530	0845	1220	1420			
	ΔPV	1.218	1.327	1.283	1.17			
	PAD	33.9	33.87	32.87	35.3			
	PN - 1	33.28	33.58	32.63	35.1			
	ΔPN - 1	31.22	29.62	26.97	25.43			
	PN - 2	11.64	11.08	10.77				
	ΔPN - 2	12.86	14.53	13.53	17.87			
	PNIS - 2	-1.1	-2.2	-2.4	-2.6			
	PNOS - 2	-.4	-.4	-.8	-.4			
	PCS	.7	.7	.7	.7			
	PCOS	.1	.1	.1	.1			
	PINJ - 1	19	17	18	21			
	PINJ - 2	9	6	6	5			
	PBAR	29.55	29.637	29.59	29.58			
	TAD	276	284	284	266			
	TN - 1	252	259	261	243			
	TN - 2	151	155	157	158			
	TCO	131	141	142	157			
	TCW	163	163.7	163	166			
	TINJ	69	69.3	70	71			
	QCW GPM	15	7	7	7			
	QINJ - 1 GPM	11.46	10.38	10.9	8.26			
	QINJ - 2 GPM	10.44	9.875	10.45	6			
	DN - 1	3.15	3.15	3.15	3.15			
	DN - 2	3.55	3.55	3.55	3.55			
	INJ NOZ - 1	16V10	16V10	16V10	16V10			
	INJ NOZ - 2	16V15	16V15	16V15	16V15			

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TANDEM NOZZLE SUPERSUB HYDRO

DATA NOMENCLATURE

The data nomenclature of the Tandem Nozzle Hydro can be used for the data for the Tandem Nozzle SuperSub Hydro with the following additions and deletions.

ADDITIONS

PST	Steam pressure at steam supersonic nozzle inlet in psig.
TST	Steam temperature in degrees Fahrenheit.
QINJSN.	Water flow, in GPM, to the water injection ring surrounding the exit of the supersonic steam nozzle.
DNST.	Diameter in inches, .188, of the supersonic steam nozzle throat.

DELETIONS

ΔPN-1	Differential pressure across the first subsonic nozzle, inches of water gage.
TN-1.	Temperature of inlet gas of the first subsonic nozzle, degrees Fahrenheit.

R & D DATA SHEET

PAGE 1 OF 1

LOCATION ENSCO, ELDORADO, ARK MODEL 100 TANDEM SUPER SUB HYDRO DATE

Decimal No.							REMARKS
RUN	113	114	115	117	118		
DATE	3/21/84	3/22/84	3/22/84	3/23/84	3/23/84		DN ST .188" INCHES
TIME	1610	0835	1130	0915	1245		FOR ALL RUNS
ΔPV	1.333	1.278	1.33	1.35	1.43		
PAD	34.5	32.7	31.76	34.8	34.4		
PN - 1	34.3	32.4	31.3	34.5	34.0		
PN - 2	13.9	12.69	13.26	16.92	16.9		
ΔPN-2	16.47	16.66	16.48	18.74	19.37		
PNIS - 2	-2.6	-2.7	-3.0	-2.3	-2.7		
PNOS - 2	-.5	-.5	-.6	-.5	-.6		
PCS	.6	.6	.6	.8	.7		
PCOS	.1	.1	.1	.1	.1		
PINJ - 1	20.7	20.2	15	26	18.3		
PINJ - 2	6.7	6.6	6.9	18.8	14		
PST	110	110	110	110	110		
PBAR	29.51	29.66	29.64	29.63	29.58		
TAD	277	289	290	303	298		
TN - 2	154	158	161	149	149		
TCO	141	144	148	135	131		
TEW	163	165	167	165	165		
TINJ	70	69.2	71	70	70		
TST	339	339	338	335	340		
QCW	7	7	7	5.4	5		
QINJ - 1	11.4	11.52	7.39	10.32	9		
QINJ - 2	10.5	10.2	10.47	10.5	11.25		
QIWSN	1.8	1.8	1.69	1.46	1.8		
DN - 1	3.15	3.15	3.15	3.15	3.15		
DN - 2	3.55	3.55	3.55	3.55	3.55		
INJ NOZ - 1	16V10	16V10	16V10	16V10	16V10		
INJ NOZ - 2	16V15	16V15	16V15	16V15	16V15		

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TANDEM NOZZLE HYDRO AND TANDEM NOZZLE SUPERSUB HYDRO

NOTES ON METHODS OF CALCULATION

1. The moisture at the inlet of inlet gas venturi, WVV, in pounds of water vapor per pound of dry gas, was calculated by a heat balance since the gas was quenched upstream of the fan and the inlet gas venturi:

Run	WVA
110	.257
111	.191
112	.241
113	.280
114	.175
115	.127
116	.204
117	.201
118	.19

2. Notes 2 through 7 of the Notes on the Methods of Calculation of the Steam Hydro apply to the Tandem Nozzle Hydro and the Tandem Nozzle SuperSub Hydro.

8. Dry gas composition by volume and weight

	Volume Fraction			Molecular Weight	Weight Fraction		
Run	CO_2	O_2	N_2	Dry Gas	CO_2	O_2	N_2
110	.061	.128	.811	29.501647	.091	.1388	.7702
111	.051	.134	.815	29.36501	.0764	.146	.7776
112	.061	.124	.815	29.48571	.091	.1346	.7744
113	.069	.120	.811	29.597735	.1026	.1297	.7677
114	.063	.125	.812	29.521685	.0939	.1355	.7706
115	.046	.139	.815	29.305546	.0691	.1518	.7791
116	.058	.139	.815	29.44171	.0867	.1359	.7774
117	.060	.134	.806	29.509556	.0895	.1453	.7652
118	.058	.125	.817	29.44171	.0867	.1359	.7774

9. Run numbers identified with sampling tests

Run	Sampling Test No.
110	10
111	11
112	12
113	13
114	14
115	15
116	16
117	17
118	18

10. The subsonic nozzle calculations for the first subsonic nozzle were not calculated for the SuperSub runs. Steam was injected into the gas stream in front of this nozzle at a location aft of PN-1, TN-1, and the front leg of the ΔPN-1 measure, thereby invalidating any calculations of the calculated nozzle parameters from these data.

TANDEM NOZZLE HYDRO AND TANDEM NOZZLE SUPERSUB HYDRO

METHODS OF CALCULATION

1. All pressures measured in inches of water gage, except differential pressures were converted to absolute pressures by the following equation:

   $PX = PBAR \times .49116 + .03605 \times PXG$

   PXG = pressure in inches of water gage

2. The weight of moisture in the gas stream at the inlet venturi WVV, in pounds of water vapor per pound of dry gas, was taken from (1) of the Notes on Methods of Calculation.

3. The weight of gas at the inlet gas venturi, WGV, in pounds per minute was calculated as follows:

$$WGV = \frac{Cd \times Fa \times \pi \times D^2 \times 60}{4 \times 144} \sqrt{\frac{2 \times g \times 144 \times \frac{\gamma}{(\gamma - 1)} \times \frac{P_1}{\rho_1} \times \left[1 - \left(\frac{P_2}{P_1}\right)^{\frac{\gamma - 1}{\gamma}}\right]}{\left[1 - \left(\frac{P_2}{P_1}\right)^{\frac{2}{\gamma}} \times \beta^4\right]}}$$

$Cd = .985$ flow coefficient

$$Fa = \left[\frac{(1 + TAD \text{ x } .0000092)}{(1 + 70 \times .0000092)}\right]^2$$

$g = 32.174$ ft/sec^2

$\pi = 3.141593$

$D = 6.138$ diameter in inches of venturi throat

$\gamma = \gamma GV = (\gamma DG + WVV \times \gamma H_2O)/(1 + WVV)$

WVV from (2) above

$\gamma DG = \chi CO_2 \times \gamma CO_2 + \chi O_2 \times \gamma O_2 + \chi N_2 \times \gamma N_2$

χCO_2 = weight fraction CO_2 in dry gas

γCO_2 = gamma of Co_2 @ TAD

χO_2 = weight fraction of O_2 in dry gas

γO_2 = gamma of O_2 @ TAD

χN_2 = weight fraction of N_2 in dry gas

γN_2 = gamma of N_2 @ TAD

γH_2O = gamma of water vapor @ TAD

P_1 = PAD in psia

P_2 = PAD - ΔPV × .03605

β = 6.138/8.316 from (5) of Notes on Methods of Calculations

$\rho = \rho GV = PAD \times 144/[RG \times (459.688 + TAD)]$

$$RG = \frac{RDG + RV \times WVV}{(1 + WVV)}$$

RDG = 1545.325 ÷ MWDG

MWDG = molecular weight of dry gas from (8) Notes on Methods of Calculation

$$RV = \frac{PAD \times VV \times 144}{(459.688 + TAD)}$$

VV = specific volume of water vapor at PAD and TAD

4. The weight of dry gas at the inlet gas venturi, WDGV, in pounds per minute was calculated as follows:

WDGV = WGV/(1 + WVV)

WGV from (3) above

WVV from (2) above

5. The volume of gas flow at the inlet gas venturi, QGV, in actual cubic feet per minute was calculated as follows:

$QGV = WGV/\rho GV$

WGV from (3) above
ρGV from (3) above

6. The volume of dry gas at the inlet gas venturi, QDGV, in standard dry cubic feet per minute was calculated as follows:

$QDGV = WDGV/\rho STD$

WDGV from (4) above

ρSTD = specific weight of dry gas at 14.696 psia and 68°F

$$= \frac{14.696 \times 144 \times MWDG}{1545.325 \times 527.688}$$

7. The specific weight of gas at the inlet gas venturi, ρGV, in pounds per cubic foot, was calculated in (3) above.

8. The ratio of the specific heats at the inlet venturi, γGV, was calculated as shown in (3) above.

9. The weight of cooling water injected into the gas stream in the quench chamber, WCW, in pounds per minute, was calculated as follows:

$WCW = QCW \times DCW$

DCW = density of water in pounds per gallon at TCW

10. The cooling water rate of injection to the quench chamber, αCW, in pounds per pound of inlet gas was calculated as follows:

$\alpha CW = WCW/WGV$

WCW from (9) above

WGV from (3) above

Calculations No. 11 through 14 apply only to the Tandem Nozzle SuperSub Tests (Runs 113, 114, 115, 117, and 118).

11. The steam flow through the supersonic steam nozzle, WST, in pounds per minute, was calculated at the nozzle throat as follows:

$WST = A \times V \times Fa \times 60/(144 \times Vg)$

A = area steam nozzle throat = $\pi \times \overline{DNST}^2/4$

DNST = .188 inches = throat diameter.

$Fa = \left[\frac{(1 + .00000092 \times TST)}{(1 + .0000092 \times 70)}\right]^2$ = temperature area coefficient of expansion

V = velocity of steam in ft/sec = $\sqrt{778.3 \times 2g \times \Delta h}$

778.3 ft lb = 1 Btu

$g = 32.174$ ft/sec^2

$\Delta h = (H_1 - H_2) \times \overline{.965}^2$

H_1 = Btu per pound of dry saturated steam at PSTA

H_2 = Btu per pound of steam at quality X_2 and throat pressure PTH

$PSTA = PST + .49116 \times PBAR$

$PTH = [\gamma/(\gamma + 1)] \times PSTA$

γ = gamma of dry saturated steam at PSTA

$X_2 = (S1 - Sf2)/Sfg2$

S1 = entropy of dry saturated steam at PSTA

Sf2 = entropy of liquid at PTH

Sfg2 = entropy of evaporation at pressure PTH

$H_2 = hf2 + X_2 \times hfg2$

hf2 = enthalpy of liquid at PTH

hfg2 = enthalpy of evaporation at PTH

$H2ACT = H_1 - \Delta h$

Quality of steam at PTH = $(H2ACT - hf2) \div hfg2 = XTH$

$Vg = Vf + XTH\ (Vg - Vf)$

Vf = volume of liquid at PTH dry saturated

Vg = volume of steam vapor at PTH dry saturated

12. The steam rate to the supersonic steam nozzle, αST, in pounds per pound of inlet venturi gas was calculated as follows:

$\alpha STM = WST/WGV$

WST from (11) above

WGV from (3) above

13. The weight of water injected at the supersonic steam nozzle exit, WINJSN, in pounds per minute was calculated as follows:

$$\mathrm{WINJSN} = \mathrm{QINJSN} \times \mathrm{DINJSN}$$

DINJSN = density of water in pounds per gallon at TINJ

14. The water injection rate at the supersonic steam nozzle exit, αINJSN, in pounds per pound of inlet venturi gas was calculated as follows:

$$\alpha\mathrm{INJSN} = \mathrm{WINJSN}/\mathrm{WGV}$$

WINJSN from (13) above

WGV from (3) above

Calculations numbers 15 thru 20 do not apply to the Tandem Nozzle SuperSub tests (Runs 113, 114, 115, 117, and 118).

15. The weight of water vapor at the inlet of the first subsonic nozzle, WVN1, in pounds per pound of dry gas, was equal to WVV from (2) above.

16. The weight of gas entering the first subsonic gas nozzle, WGN1, in pounds per minute, was equal to WGV, from (3) above.

17. The specific weight of the gas entering the first subsonic gas nozzle, ρGN1, in pounds per cubic foot, was calculated as follows:

$$\rho\mathrm{GN1} = \mathrm{PN1} \times 144/[\mathrm{RG} \times (\mathrm{T} + 459.668)]$$

T = TN1

$$\mathrm{RG} = (\mathrm{RDG} + \mathrm{WVN1} \times \mathrm{RV})/(1 + \mathrm{WVN1})$$

$$\mathrm{RDG} = 1545.325/\mathrm{MWDG}$$

MWDG from (8) of Notes on Methods of Calculations

WVN1 from (15) above

$$\mathrm{RV} = \frac{\mathrm{P} \times \mathrm{VV} \times 144}{(\mathrm{T} + 459.688)}$$

P = PN1 T = TN1

VV = specific volume of water vapor cubic feet per pound at PN1 and TN1

18. The ratio of the specific heats of the gas entering the first subsonic gas nozzle, $\gamma GN1$, was calculated as follows:

$\gamma GN1 = (\gamma DG + WVN1 \times \gamma H_2O)/(1 + WVN1)$

$\gamma DG = \chi CO_2 \times \gamma CO_2 + \chi O \times \gamma O_2 + \chi N_2 \times \gamma N_2$

χCO_2 = weight fraction CO_2 in dry gas

γCO_2 = gamma of CO_2 at TN1

χO_2 = weight fraction of O_2 in dry gas

γO_2 = gamma of O_2 at TN1

χN_2 = weight fraction of N_2 in dry gas

γN_2 = gamma of N_2 at TN1

WVN1 from (15) above

γH_2O = gamma of water vapor at temperature TN1

19. The specific weight of gas at the throat of the first subsonic gas nozzle, $\rho GNT1$, in pounds per cubic foot was calculated as follows:

$$\rho GNT1 = \left(\frac{P_2}{P_1}\right)^{\frac{1}{\gamma}} \times \rho GN1$$

$P2 = PN1 - .03605 \times \Delta PN1$

$\gamma = \gamma GN1$ from (18) above

$\rho GN1$ from (17) above

$P1 = PN1$

20. The velocity at the throat of the first subsonic gas nozzle, VGNT1, in feet per second, was calcualted as follows:

$$VGN1 = \sqrt{2\ g \times 144 \times \frac{P_1}{\rho_1} \times \frac{\gamma}{\gamma - 1} \times \left[1 - \left(\frac{P_2}{P_1}\right)^{\frac{\gamma - 1}{\gamma}}\right] \Bigg/ \left[1 - \left(\frac{P_2}{P_1}\right)^{\frac{2}{\gamma}} \times \beta^4\right]}$$

$g = 32.174\ ft/sec^2$

$P1 = PN1$

$\rho 1 = \rho GN1$ from (17) above

$\gamma = \gamma GN1$ from (18) above

P2 from (19) above

$\beta = \text{DN1}/\text{DNUP1}$

DN1 = exit diameter first subsonic gas nozzle

DNUP1 = 6.0625 upstream diameter of the first subsonic gas nozzle.

21. The weight of water injected around the circumference of the exit of the first subsonic gas nozzle, WINJ1, in pounds per minute was calculated as follows:

$\text{WINJ1} = \text{QINJ1} \times \text{DINJ}$

DINJ = density of water in pounds per gallon at TINJ

22. The water rate of injection at the exit of the first subsonic gas nozzle exit, α INJ1, in pounds per pound of inlet venturi gas was calculated as follows:

$\alpha\text{INJ1} = \text{WINJ1}/\text{WGV}$

WINJ1 from (21) above

WGV from (3) above

23. The weight of water vapor in the gas stream entering the second subsonic gas nozzle, WVN2, in pounds per pound of dry gas, was calculated as follows:

$\text{WVN2} = \text{pv} \times 18.016 / [\text{MWDG} \times (\text{PN2} - \text{pr})]$

pv = water vapor pressure at TN2

MWDG = molecular weight of dry gas from (8) of Notes on Methods of Calculations

24. The weight of gas entering the second subsonic gas nozzle, WGN1, in pounds per minute, was calculated as follows:

$\text{WGN2} = (1 + \text{WVN2})\ \text{WDGV}$

WVN2 from (23) above

WDGV from (4) above

25. The specific weight of gas entering the second subsonic gas nozzle, ρGNZ, in pounds per cubic foot, was calculated as follows:

$$\rho GN2 = \frac{P \times 144}{RG \times (T + 459.688)}$$

$P = PN2$

$T = TN2$

$$RG = \frac{(RDG + WVN2 \times RV)}{(1 + WVN2)}$$

WVN2 from (23) above

$RDG = 1545.325/MWDG$

MWDG from (8) of Notes on Methods of Calculation

$$RV = \frac{PN2 \times VV \times 144}{(TN2 + 459.688)}$$

VV = specific volume of water vapor at PN2 and TN2

26. The ratio of the specific heats of the gas entering the second subsonic nozzle, $\gamma GN2$, was calculated as follows:

$\gamma GN2 = (\gamma DG + WVN2 \times \gamma H_2O)/(1 + WVN2)$

WVN2 from (23) above

$\gamma DG = \chi CO_2 \times \gamma CO_2 + \chi O_2 \times \gamma O_2 + \chi N_2 \times \gamma N_2$

χCO_2 = weight fraction CO_2 in dry gas

γCO = gamma of CO_2 at TN2

χO_2 = weight fraction O_2 in dry gas

γO_2 = gamma of O_2 at TN2

χN_2 = weight fraction N_2 in dry gas

γN_2 = gamma of N_2 at TN2

γH_2O = gamma of water vapor at TN2

27. The specific weight of the gas at the throat (exit) of the second subsonic gas nozzle, GNT, in pounds per cubic foot, was calculated as follows:

$$\rho GNT = \left(\frac{P_2}{P_1}\right)^{\frac{1}{\gamma}} \times \rho GN2$$

$P_2 = P_1 - .03605 \times \Delta PN2$

$P_1 = PN2$

$\gamma = \gamma GN2$ from (26) above

$\rho GN2$ from (25) above

28. The velocity at the throat (exit) of the second subsonic gas nozzle, VGNT2, in feet per second, was calculated as follows:

$$VGNT2 = \sqrt{2g \times 144 \times \frac{P_1}{\rho_1} \times \frac{\gamma}{\gamma - 1} \times \left[1 - \left(\frac{P_2}{P_1}\right)^{\frac{\gamma - 1}{\gamma}}\right] \Big/ \left[1 - \left(\frac{P_2}{P_1}\right)^{\frac{2}{\gamma}} \times \beta\right]}$$

$g = 32.174$ ft/sec^2

P1 - PN2

$\frac{P_2}{P_1}$ from (27) above

$\gamma = \gamma GN2$ from (26) above

$\rho 1 = \rho GN2$ from (25) above

$\beta = DN2/DNUP2$

DN2 = exit diameter of the second subsonic gas nozzle

DNUP2 = upstream diameter of the second subsonic gas nozzle = 6.0625 inches

29. The weight of water injected into the gas stream at the circumference of the exit of the second subsonic gas nozzle, WINJ2, in pounds per minute, was calculated as follows:

WINJ2 = QINJ2 × DINJ

DINJ ÷ Density of water in pounds per gallon at TINJ

30. The water rate of injection at the exit of the second subsonic gas nozzle, αINJ2, in pounds per pound of inlet venturi gas was calculated as follows:

αINJ2 = WINJ2/WGV

WINJ2 from (29) above

WGV from (3) above

31. The total water injected in the gas cleaner, αTW, pounds per pound of inlet venturi gas, was calculated as follows:

a. Tandem Nozzle Hydro

αTW = αCW + αINJ1 + αINJ2

αCW from (10) above

αINJ1 from (22) above

αINJ2 from (30) above

b. Tandem Nozzle SuperSub Hydro

αTW = αCW + αST + αINJSN + αINJ1 + αINJ2

αCW from (10) above

αST from (12) above

αINJSN from (14) above

αINJ1 from (22) above

αINJ2 from (30) above

32. The weight of water vapor in the exit gas stream, WVEX, in pounds per pound of dry gas, was calculated as follows:

WVEX = pv x 18.016/ [MWDG × (PEX - pv)]

pv = water vapor pressure at TEX

18.016 = molecular weight of water vapor

MWDG = molecular weight of dry gas from (8) of Notes on Methods of Calculations.

$PEX = PCOS \times .03605 + PBAR \times .49116$

$TEX = TCO$

33. The weight of the exit gas stream, WGEX, in pounds per minutes, was calculated as follows:

$WGEX = (1 + WVEX) \times WDGV$

WVEX from (32) above

WDGV from (4) above

34. The specific weight of the gas at the exit, ρGEX, in pounds per cubic foot, was calculated as follows:

$$\rho GEX = \frac{PEX \times 144}{RGEX \times (TEX + 459.688)}$$

PEX from (32) above

TEX from (32) above

$RGEX = (RDG + RVEX \times WVEX)/(1 + WVEX)$

RDG from (25) above

$$RVEX = \frac{PEX \times 144 \times VV}{(459.688 + TEX)}$$

VVEX = specific volume of water vapor at PEX and TEX

35. The volume of the exit gas, QGEX, in actual cubic feet per minute, was calculated as follows:

$QGEX = WGEX/\rho GEX$

WGEX from (33) above

ρGEX from (34) above

ENSCO ELDORADO ARK.
TANDEM NOZZLE HYDRO

SHEET 1 OF 2

RUN	110	111	112	116
DATE	3/20/84	3/21/84	3/21/84	3/22/84
TIME	1530	0845	1220	1420
ΔPV	1.218	1.327	1.283	1.17
PAD	15.718	15.777	15.718	15.468
TAD	276	284	284	266
WGV	67.01	70.15	68.33	66.66
WVV	.257	.191	.241	.204
WDGV	53.31	58.90	55.06	55.37
QGV	1278	1332	1352	1233
QDGV	699	776	722	727
ρGV	.05252	.05284	.0518	.0541
γGV	1.364	1.3727	1.369	1.3718
QCW	15	7	7	7
WCW	122.19	57.01	57.04	58.29
αCW	1.829	.813	.835	.874
PN1	15.714	15.767	15.71	15.794
ΔPN1	31.22	29.62	26.97	25.43
TN1	252	259	261	243
WVN1	.257	.191	.241	.204
WGN1	67.01	70.15	68.33	66.66
ρGN1	.05408	.05473	.0535	.05638
γGN1	1.3654	1.3739	1.3701	1.3730
ρGNT1	.05121	.05200	.05106	.05346
VGNT1	461	446	430	408
QINJ1	11.46	10.38	10.9	8.25
WINJ1	95.46	86.41	90.78	67.13
αINJ1	1.426	1.173	1.33	1.007

ENSCO ELDORADO ARK
TANDEM NOZZLE HYDRO

SHEET 2 OF 2

RUN	110	111	112	116				
DATE	3/20/84	3/21/84	3/21/84	3/22/84				
TIME	1530	0845	1220	1420				
DN1	3.155	3.155	3.155	3.155				
DNUP1	6.0625	6.0625	6.0625	6.0625				
PN2	14.933	14.956	14.922	15.061				
ΔPN2	12.86	14.53	13.53	17.87				
TN2	151	155	157	158				
WVN2	.21486	.23267	.25692	.27059				
WGN2	64.70	72.61	69.22	70.34				
ρGN2	.06087	.06002	.05925	.05939				
γGN2	1.3715	1.3764	1.3739	1.3737				
ρGNT2	.05948	.05848	.05783	.05753				
VGNT2	277	296	392	339				
QINJ2	10.44	9.875	10.45	6				
WINJ2	86.96	82.25	87.03	48.82				
αINJ2	1.298	1.173	1.274	.733				
DN2	3.55	3.55	3.55	3.55				
DNUP2	6.0625	6.0625	6.0625	6.0625				
αTW	4.553	3.219	3.456	2.614				
PEX	14.517	14.560	14.537	14.532				
TEX	131	141	142	157				
WVEX	.1171	.15546	.16408	.27396				
WGEX	59.53	68.07	64.09	70.53				
ρGEX	.06363	.06149	.06122	.05731				
QGEX	936	1108	1047	1232				

ENSCO ELDORADO ARK.
TANDEM NOZZLE SUPER-SUB

SHEET 2 OF 2

RUN	113	114	115	117	118			
DATE	3/21/84	3/22/84	3/22/84	3/22/84	3/22/84			
TIME	1610	0835	1130	0915	1245			
PN1	3.15	3.15	3.15	3.15	3.15			
DNUP1	6.0625	6.0625	6.0625	6.0625	6.0625			
PN2	14.995	15.061	15.085	15.163	15.139			
ΔPN2	16.47	16.66	16.48	18.74	19.37			
TN2	154	158	161	149	149			
WVN2	.22935	.25866	.29729	.19324	.18919			
WGN2	66.87	73.87	81.63	69.73	72.46			
ρGN2	.06062	.05976	.05856	.06248	.06296			
γGN2	1.3739	1.3735	1.3743	1.3769	1.3774			
ρVNT2	.05886	.05801	.05681	.06045	.06084			
VGNT2	322	326	327	338	343			
QINJ2	10.5	10.2	10.47	10.5	11.25			
WINJ2	87.45	84.96	87.19	87.45	93.70			
αINJ2	1.256	1.232	1.229	1.247	1.293			
DN2	3.55	3.55	3.55	3.55	3.55			
DNUP2	6.0625	6.0625	6.0625	6.0625	6.0625			
αTW	3.695	3.709	3.162	3.313	3.135			
PEX	14.498	14.571	14.561	14.557	14.582			
TEX	141	144	148	135	131			
WVEX	.15625	.17372	.19892	.12817	.11172			
WGEX	62.90	68.93	75.45	65.93	67.73			
ρGEX	.06161	.06096	.05814	.06341	.06442			
QGEX	1021	1131	1298	1040	1051			

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ENSCO ELDORADO ARK.
TANDEM NOZZLE SUPER-SUB

SHEET 1 OF 2

RUN	113	114	115	117	118			
DATE	3/21/84	3/22/84	3/22/84	3/23/84	3/23/84			
TIME	1610	0835	1130	0915	1245			
ΔPV	1.333	1.278	1.33	1.35	1.43			
PAD	15.743	15.747	15.702	15.808	15.769			
TAD	277	289	290	303	298			
WGV	69.70	68.96	70.92	70.18	72.49			
WVV	.280	.175	.127	.201	.19			
WDGV	54.40	58.69	62.93	58.43	60.92			
QGV	1344	1302	1318	1352	1389			
QDGV	711	769	825	761	795			
ρGV	.05179	.05296	.05383	.05192	.05219			
γGV	1.3365	1.3711	1.3764	1.3698	1.3710			
QCW	7	7	7	5.4	5			
WCW	57.02	56.99	56.96	43.96	40.7			
αCW	.819	.826	.803	.628	.562			
PSTA	124.5	124.5	124.5	124.5	124.5			
TST	339	338	338	335	340			
WST	2.829	2.829	2.829	2.829	2.829			
DNST	.188	.188	.188	.188	.188			
αST	.041	.041	.040	.040	.039			
QINJSN	1.8	1.8	1.69	1.46	1.8			
WINJSN	14.99	14.99	14.07	12.16	14.99			
αINJSN	.215	.218	.198	.173	.207			
PN1	15.73	15.735	15.696	15.795	15.755			
QINJ1	11.4	11.52	7.59	10.32	9			
WINJ1	94.84	95.95	63.21	85.95	74.96			
αINJ1	1.364	1.392	.841	1.225	1.034			

DRY SCRUBBER CONTROL OF HAZARDOUS WASTE INCINERATOR EMISSIONS

(A Pilot Study)

July 1984

ETS, inc.

Suite C-103

3140 Chaparral Dr., SW

Roanoke, VA 24018

ETS, INC. CONTRACT NO.: 84-363-T

Pollution Control Consultants
Specializing In
Fabric Filtration and Sulfur Dioxide Removal

I. Introduction

The ETS dry scrubbing system was tested on an exhaust gas slipstream from a hazardous waste incinerator at the ENSCO facility, El Dorado, Arkansas.

The dry scrubbing system was installed during the last week of March, 1984. The system was operated and tested during two separate periods, April 1-10 and April 23-26.

Two reactant materials (hydrated lime and nahcolite) were studied for chloride removal effectiveness. In addition, system particulate removal efficiency was determined.

All testing was conducted by Engineering Science, ETS was responsible for system operation while Research Triangle Institute provided program direction and management.

II. The Dry Scrubbing System

The slipstream was withdrawn ahead of ENSCO's flue gas wet scrubbing system through a port on the side of the emergency bypass. The gases were prequenched to a temperature of about 550°F before delivery to the pilot system. Gas flows (measured at the dry scrubber inlet) ranged from 370 to 1300 ACFM. A process schematic is shown in Figure 1.

Referring to Figure 2, the Dry Reactor's basic operating principles are as follows: flue gas is directed cyclonically into the reactor where the rotating slinger unit delivers the dry reactant perpendicular to the flue gas, thus creating maximum mixing, and intimate contact of the reactant and pollutant. An internal recirculator with no moving parts is located above the slinger, thus increasing the contact time, and thereby enhancing HCl removal.

The slinger then directs the resulting dry compounds down and into an expansion section where a portion of the compounds are removed. The finer particulate pollutants and additional HCl are removed by a pulse jet cartridge type baghouse employing Nomex fabric. The cleaned gas is then delivered to the atmosphere.

III. Discussion of Results

During the course of the program two reactants were studied; hydrated lime and nahcolite. The hydrated lime is a commercially available material supplied by Arkansas Lime, Batesville, Arkansas. The nahcolite was obtained from the Bureau of Mines and contained less than 55% sodium bicarbonate. A chemical analysis for each material is shown in Table 1.

Test parameters for the hydrated lime runs are presented in Table 2 while nahcolite run parameters are shown in Table 3. Essentially both materials were tested at 0.6 and 1.2 lbs/minute feed rate. Gas temperatures were measured at the inlet and outlet sampling location as well as at the point of sorbent introduction (reactor).

There was a great deal of heat loss through the system. Because of these losses baghouse temperatures were routinely below those that would be recommended for reliable system operation. It is believed that these low temperatures were at least in part responsible for some of the baghouse operational problems experienced during the test program. Operation at temperatures less than 260°F should provide low chloride emissions, however, at the same time cause high levels of $CaCl_2$ to be present in the filter cake. $CaCl_2$ is hydroscopic, thus causing bag cleaning problems resulting in high pressure drop and low gas flow.

Operation at high baghouse temperatures ($\approx$320°F) would have alleviated this problem, however, this was not possible due to inadequate insulation on the reactor, connecting ductwork and baghouse.

Chloride removal efficiencies are presented in Table 4. From these runs it appears that hydrated lime offers the best potential or chloride control. It should be noted that equipment restrictions did not enable us to test nahcolite at stoichmetric rates above 1.7/1.

Particulate removal efficiencies are shown in Table 5. Data after the tenth run is questionable; as at least one filter cartridge was found to have failed at that point.

TABLE 1

Chemical Composition of Material
used in ENSCO TESTS

	Hydrated Lime
$CA(OH)_2$	94.75
$CaCO_3$	1.36
Water	0.56
Inerts	3.33

	Nahcolite
$NaHCO_3$	52.76
$NaCO_3$	3.5
NaCl	0.49
Na_2SO_4	0.4
Na_2SO_3	0.001
$NaNO_3$	0.02
Insolubles	40.86
Water	1.83

Both materials were 100% - 200 mesh

TABLE 2

Hydrated Lime

Run No.	Date	Temperature °F In	Temperature °F React	Temperature °F Out	ACFM In	ACFM Out	HCL Conc PPM	Lime Feed #1 Min.	SR $\frac{Ca(OH)_2}{HCL}$	System Δp
1	4-4-84	540	350	178	745	919	11200	1.2	1.47	-
2	4-4-84	622	350	194	632	745	8500	1.2	2.43	-
3	4-4-84	532	300	168	622	844	9100	1.2	2.14	-
4	4-5-84	464	300	162	471	782	6800	1.2	3.31	2.4
5	4-5-84	457	225	148	377	778	6200	1.2	4.80	3.6
6	4-5-84	385	225	151	481	650	4800	1.2	5.93	3.8
7	4-6-84	345	220	129	514	608	3300	0.6	2.95	3.5
8	4-10-84	559	395	214	801	942	7400	0.6	0.93	1.5
9	4-10-84	478	350	195	641	693	7000	0.6	1.21	2.7

TABLE 1

Nahcolite

Run No.	Date	Temperature ^oF In	React	Out	ACFM In	Out	HCL Conc PPM	NAH Feed #1 Min.	SR $\frac{NaHCO_3}{HCL}$	System Δ p
10	4-10-84	363	245	143	372	471	9600	0.6	.718	3.0
11	4-24-84	683	430	301	1394	1238	4470	0.6	.550	-
12	4-25-84	604	380	202	836	932	4280	0.6	.892	7.4
13	4-25-84	660	340	236	859	745	-	0.6	-	7.5
14	4-26-84	555	375	219	766	637	6870	0.6	.609	7.5
15	4-26-84	453	320	216	779	890	4160	1.26	1.770	7.0
16	4-26-84	611	340	225	779	790	8570	1.26	1.009	7.0

TABLE 4

ETS BAGHOUSE

CHLORIDE REMOVAL EFFICIENCY

Run No.	Date	Inlet Loading (lbs/hr)	Outlet Loading (lbs/hr)	System Efficiency (%)
1	4-4-84	23.1580	0.3112	98.656
2	4-4-84	14.6038	1.5994	89.048
3	4-4-84	14.7309	0.2925	98.014
4	4-5-84	9.9603	0.0820	99.177
5	4-5-84	7.5713	0.0857	98.868
6	4-5-84	8.1725	0.0355	99.566
7	4-6-84	6.2290	0.0133	99.786
8	4-10-84	16.9886	7.4234	56.304
9	4-10-84	13.5912	2.8466	79.056
10	4-10-84	12.5841	0.8498	93.247
11	4-24-84	16.4313	2.9566	82.006
12	4-25-84	10.1211	4.5798	54.750
13	4-25-84	*	7.2524	-
14	4-25-84	15.5858	7.2058	53.767
15	4-26-84	10.7201	3.4226	68.073
16	4-26-84	18.8044	12.5758	33.123

* Sample bottle was broken before sample was analyzed.

TABLE 5

ETS BAGHOUSE
PARTICULATE REMOVAL EFFICIENCY

Run No.	Date	Inlet Loading (lbs/hrs)	Outlet Loading (lbs/hrs)	System Efficiency (%)
1	4-4-84	1.3982	0.1245	91.096
2	4-4-84	1.6154	0.0429	97.344
3	4-4-84	1.7194	0.0651	96.214
4	4-5-84	0.8730	0.0455	94.788
5	4-5-84	0.7919	0.0406	94.873
6	4-5-84	3.4919	0.0584	98.328
7	4-6-84	0.7483	0.0740	90.111
8	4-10-84	1.6267	0.0389	97.609
9	4-10-84	5.2948	0.1039	98.038
10	4-10-84	2.5023	0.0998	96.012
11	4-24-84	1.6118	3.9204	*
12	4-25-84	1.7646	0.4236	75.995
13	4-25-84	1.2128	0.3013	75.157
14	4-25-84	1.5108	0.2275	84.942
15	4-26-84	0.7783	0.1354	82.603
16	4-26-84	0.9178	0.5674	38.178

* During Run 11 on April 24 at least one bag tore in the baghouse Apparently resulting in higher outlet emissions than inlet loadings.

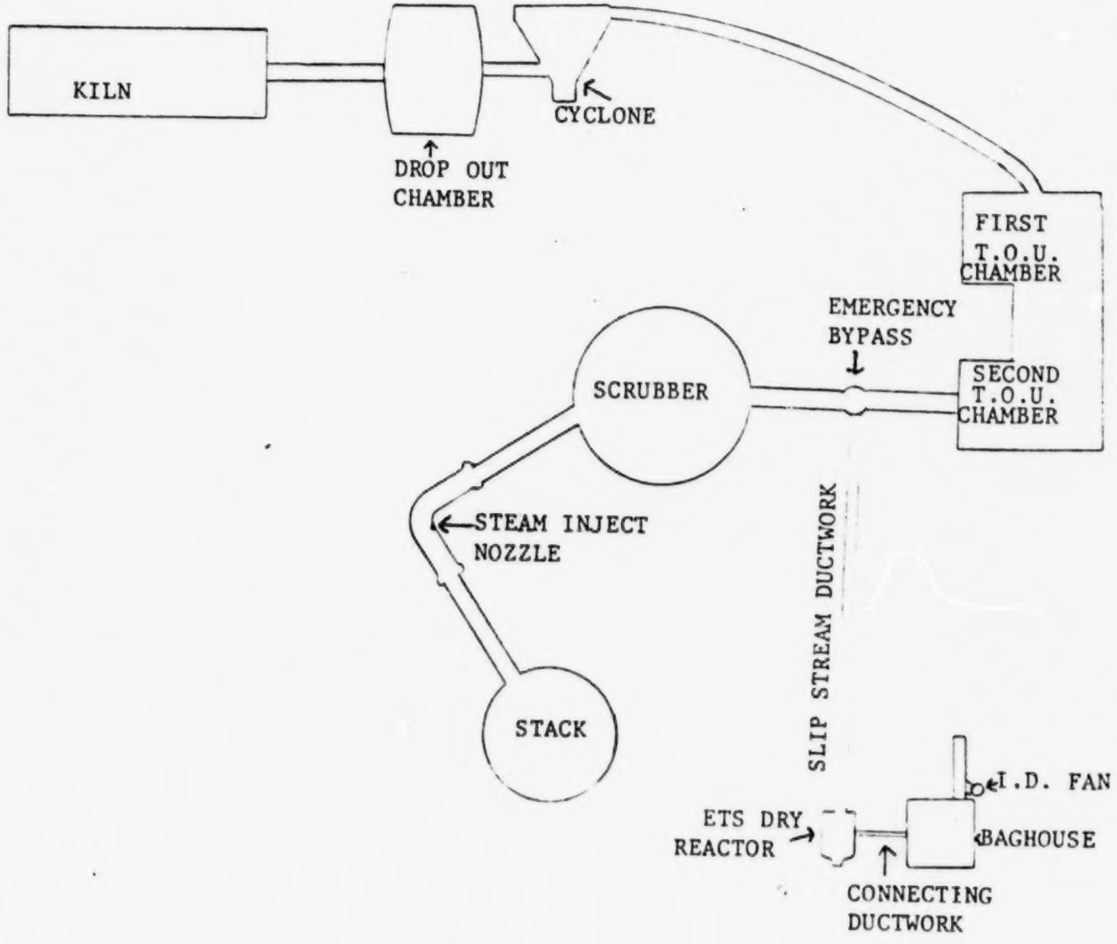
KILN
DROP OUT CHAMBER
CYCLONE
FIRST T.O.U. CHAMBER
SECOND T.O.U. CHAMBER
EMERGENCY BYPASS
SCRUBBER
STEAM INJECT NOZZLE
STACK
SLIP STREAM DUCTWORK
I.D. FAN
BAGHOUSE
ETS DRY REACTOR
CONNECTING DUCTWORK

FIGURE 1. ENSCO PROCESS AND ETS DRY SCRUBBER UNIT

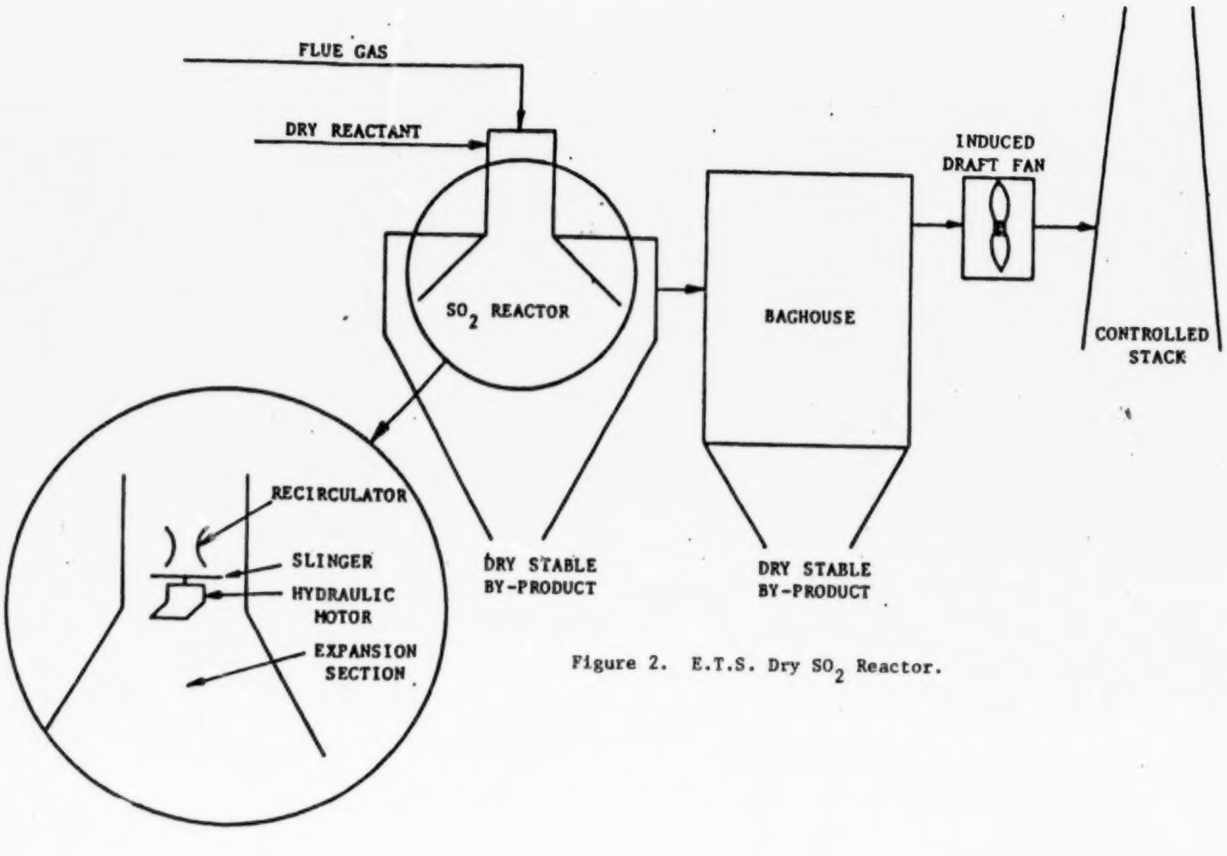
FLUE GAS
DRY REACTANT
SO_2 REACTOR
DRY STABLE BY-PRODUCT
BAGHOUSE
DRY STABLE BY-PRODUCT
INDUCED DRAFT FAN
CONTROLLED STACK
RECIRCULATOR
SLINGER
HYDRAULIC MOTOR
EXPANSION SECTION

Figure 2. E.T.S. Dry SO_2 Reactor.

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Hi-TAC Test Report

No. T-1004

August 14, 1984

Research Triangle Institute Test Program
Hazardous Waste Incineration Emission Control

May 9-25, 1984

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TABLE OF CONTENTS

I. Introduction

II. Summary

III. Test Program Description

  A. Process Description

  B. Hi-TAC Mobile Test Unit

  C. Sampling and Analysis

IV. Results and Analysis of Results

  A. Set-Up

  B. Preliminary Test Program

  C. Mechanical Problems

  D. Inleakage

  E. Particulate Test

  F. Cleaning and Pressure Drop

  G. Grain Loading

  H. HCL Removal

  I. Particle Sizing

  J. Tables - Tests 1 Through 10

  K. Tables - Inleakage Calculations

  L. Tables - Inlet Particle Sizing

  M. Tables - Outlet Particle Sizing

  N. Tables - Particulate Removal efficiency

V APPENDIX

  A. Preliminary Test Program

  B. Diagram of Hi-TAC Temperature and Pressure Sensors

  C. Plot Plan

  D. Representation of the Mobile Unit

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I. INTRODUCTION

This report concerns the Vulcan Engineering participation in a test program organized by the Research Triangle Institute and funded by the Environmental Protection Agency.

The purpose of this test program was to demonstrate the application of new technology to the dual problems of particulate and acid emissions from hazardous waste incineration.

The process central to the program was a hazardous waste incinerator owned and operated by Energy Systems Company (ENSCO) of El Dorado, Arkansas. All stack sampling and analysis was performed by the Engineering Science Company of Fairfax, Virginia.

The Hi-TAC System is primarily a particulate emission control device. The pre-coating with, and addition of, lime during this test program was an attempt to control the high HCL levels in the effluent gas stream and also protect the mobile unit from acid damage.

The test program ran May 14 - 25, 1984. The various people involved at the site were:

Vulcan Engineering Company (VEC)

Robert Casselberry, Applications Engineer

Research Triangle Institute (RTI)

Gene Tatsch, Environmental Scientist

Ensco/Ace Crown Construction (ESC)

Don Johnson

Energy Systems Company

Tom Hart, Chemist
Mike Gallagher
Larry Cottone
Dave Krask
Mike Maret
James Peters

II Summary

This test program demonstrated the Hi-TAC concept as a viable approach to the particulate and HCL emissions generated in hazardous waste incineration. It also demonstrated that Hi-TAC is capable of effectively filtering sub-micron size particulate.

The average gas temperature at the inlet to the Mobile Unit was 750 degrees F. Well above the limits allowed by conventional baghouses. The Mobile Test Unit has the capability to handle inlet gas temperatures up to 1350 degrees F.

The average air-to-filter ratio (similar to baghouse air-to-cloth ratio) was 7.9:1. The average particulate emission from the Mobile Test Unit was 0.0526 Gr/SDCF. This being the figure corrected to 50% excess air, 7% oxygen by volume as specified in pertinent air pollution control regulations.

The addition of an acid neutralizing reagent to the gas stream prior to the Hi-TAC device will control the HCL emissions. Tests Utilizing the combination of a dry scrubber/injection system with the Hi-TAC Mobile Unit should be instigated on a hazardous waste incinerator. This would prove to be an economical solution to both the fine particulate and HCL emissions.

Particulate attention should be given to Test Number 10 where the efficiency 98.4% pressure drop 8.5" W.G., and outlet grain loading 0.0234 gr/SDCF (corrected to 7% oxygen by volume, 50% excess air).

III. Description of Test Program

A. Process Description

The process at the center of this test program was the hazardous waste incinerator owned and operated by the Energy Systems Company (ENSCO) at El Dorado, AR. (See Appendix V, C. for Plot Plan).

The incinerator burns a large quantity of PVC among its feed. This results in a high level of hydrogen chloride (HCL) emissions (7,000 to 12,000 PPM at the test site).

In addition to the HCL, the location where the test ductwork tapped into the main system guaranteed a high percentage of sub-micron particulate in the gas stream.

The incinerator operated on a 24-hour basis, 7 days a week during the entire length of the Hi-TAC test.

The plant utilizes a wet scrubber system with a lime slurry for the present particulate and HCL control.

B. Hi-TAC Mobile Test Unit

The mobile test unit is part of a service which demonstrates the ability of the Hi-TAC process (High Temperature Air Cleaning) to operate under actual industrial conditions.

By performing under actual plant conditions, the unit is able to determine which set of parameters must be satisfied for a full scale Hi-TAC Unit to operate at maximum efficiency.

The Mobile Unit need only be supplied with 480V, 3 Phase, 200 Amp service with an off-take duct from the process to operate under normal conditions. For this program, a 2,000,000 BTU gas fired heater was used to provide protection against damage from acid condensation during start-up and shut-down.

B. Hi-Tac Mobile Test Unit (Continued)

The flexibility of the Mobile Unit allows for the testing of several types of filter elements, and several types of cleaning mechanisms, as detailed later.

Instrumentation of the Mobile Test Unit includes an overall unit pressure drop measurement and recording device; a 12 pt. temperature recorder with K-type thermocouples placed throughout the system to obtain a temperature profile for the unit; magnahelic pressure gauges to measure pressure drop across individual modules; and an opacity monitor on the exhaust stack.

Appendix V, D. is a representation of the Mobile Unit.

The Unit has four (4) cleaning modules - I, II, III, and IV. The modules may be isolated, using butterfly valves, so that any combination, from single module to four modules, may be used during a test.

Each module has four (4) filter elements - A, B, C, and D. These are the heart of the Hi-TAC Unit. Each element consists of a metallic reinforcing framework and a removable stainless steel woven filter.

There are many types of stainless steel weaves available. These weaves vary in the type of weave (plain square, twilled, dutch, dutch twilled, etc.), size of wire used in the weave, and the size of the openings between wires.

The selection of the correct weave for a given process is important to the success of the Hi-TAC Unit. To facilitate the selection, the Mobile Test Unit has the capacity to test four (4) sets of different weaves at the same time, one type of weave per module.

During this test program, there were three (3) types of weaves in the Unit. These were:

Module I - 150 x 150 plain weave
Module II - 325 x 325 twilled weave
Modules III & IV - 50 x 250 dutch weave

B. Hi-TAC Mobile Test Unit (Continued)

The Mobile Test Unit uses compressed air in the four types of cleaning devices built into the system. These devices are:

Modules I & II - air knives and vibrators
Modules III & IV - pulsers and rappers

The vibrators and rappers are impact devices which remove dust cake from the filters by striking the elements. The pulser uses a blast of compressed air for the same purpose. The air knife is a branched pipe which rotates within the filter element. Compressed air is forced through nozzle like openings in the branches to blow the dust cake away from the filter.

The force of the compressed air to each device is controlled by individual regulators on the Unit. Line pressure is kept at 100 PSI, and is therefore the maximum limit at which the devices will operate.

A programmable controller activates and operates the cleaning devices according to one of three methods:

1. - A timing approach when cleaning occurs at regular timed intervals.
2. - A pressure approach when cleaning occurs only when a pre-determined pressure drop across the system has been reached. (the initiating pressure drop is set by the operator prior to testing).
3. - A manual activation, according to the operator.

Length and duration of all cleaning device operations is controlled by the Programmable controller.

The Mobile Unit has the capability of isolating and cleaning individual modules, or cleaning individual filter elements while on line. Both methods were attempted during this program.

C. Sampling and Analysis

All stack sampling and analysis of the samples were performed by Engineering Science Company. Some preliminary data was provided overnight in the fields.

Details of the methods used by Engineering Science Company should be presented by their responsible personnel on this project.

IV. Results and Analysis of Results

The Following tables J, K, L, M, and N are a presentation of the results of the test program. As anyone in a research position will testify, the gathering of data is only the beginning of a project. Compilation, tabulation, and correct interpretation are often the crucial points of any program.

With a program as dynamic as the one covered in this report, a step-by-step approach will clarify results, and lead to an easier comprehension of the facts.

A. Set Up

The Mobile Test Unit (MTU) arrived at the ENSCO plant on the morning of May 9, 1984. Placing the MTU on the concrete pad where the testing was to be done proved to be more difficult than anticipated.

The MTU has a ground clearance of about 12", and while the concrete pad was flat, the road leading to it was steeply inclined. Earth moving equipment was required to construct a ramp up to the pad. Eventually a mobile derrick was required to "spot" the MTU. The remainder of May 9th and part of May 10th was required to attach the ductwork at the site.

On May 10th the electrcians could not hook-up the MTU until late in the day. At that point it was discovered that the 100 amp service to the site was insufficient for the requirements of the MTU.

Hi-TAC drawings had specified 200 amp service. An electrical contractor was be hired to run conduit and pull wire to the site. Electrical hook up was completed late afternoon of May 11th.

A. Set Up (Continued)

After completion of electrical hook-up all motors on the MTU were checked for correct rotation. The complete MTU was checked to established if any damage occurred during shipment.

The heater was used on May 12th to blow hot air through the MTU. This was done to dry the insulation on the MTU which had become saturated during thunderstorms while on the road.

The Engineering Science Company (ESC) test crew arrived on May 15th. They immediately expressed concern about the location of the exhaust test port. The area was not large enough to allow simultaneous sizing and particulate sampling.

ESC suggested installing a 9 foot vertical extension on the exhaust. The idea was seconded by Gene Tatsh of Research Triangle Institute (RTI) who was concered about dispersing the HCL that the MTU did not collect. After pulling gas through the MTU late on May 14th, the decision was reached to install the stack extension.

The extension was fabricated and installed on May 15th. A platform and scaffolding was erected for the outlet test site. Insulation was crudely attached to the extension and the transition piece leading to the MTU.

On May 16th, the ESC crew continued to set up while changes were made in the Programmable Controller of the MTU. Thereafter everything was ready to begin the test program.

B. The Preliminary Test Program

All of the participants in the program at ENSCO were asked to submit a Preliminary Test Program prior to arriving at the test site. The Hi-TAC Preliminary Test Program can be found in appendix (V,A). Unfortunately, due to time and physical restrictions it was not feasible to follow this program to any great degree.

C. Mechanical Problems

The mechanical problems encountered during the test program were few, but important enough to note. The first problem, of minor importance, was a failure of the solenoid controlling the butterfly valve which isolated module I. This meant than only on-line cleaning could be carried out in module I. And on line cleaning had proved less effective to isolation cleaning in past test programs.

The second problem was more serious. One the morning of May 18th, a routine inspection of the filter elements revealed that a 325 mesh twill filter in module II had split. The split was a result of a loose fit of the lighter material over the supporting member of the element. Creases appeared in the mesh and were "worked" by the cleaning of the mesh. Module II had to be removed from the test program. The remaining filters were of a heavier construction and not prone to this failure. However, the balance of testing was completed with the three (3) remaining modules.

D. Inleakage

After the first few runs it was obvious from the preliminary data, that there was a significant inleakage problem in the MTU. Oxygen data collected by Orsat analysis at inlet and outlet test sites indicated an inleakage of approximately 50% (See Table K) This inleakage appears to have originated around the common duct heads of each of the four filtration modules, and around the slide gates to the hoppers on the modules.

Steps were taken on May 19th to seal the possible areas of inleakage, but no apparent reduction resulted from the efforts. The time and man-power available were not sufficient to thoroughly correct the problem. Thereafter, the oxygen levels were carefully monitored and inleakage calculated for each run. All data affected by the inleakage, specifically the Grains/SDCF information, were corrected to reflect the inleakage.

This inleakage is a problem that is inherent to the construction and operation of any mobile test equipment. Road travel tends to loosen bolts and displace gasketing. A more exacting inspection and maintenance program after arriving on site must be implemented on all future tests.

E. Particulate Sizing

A particle size test was performed at the inlet and outlet site once a day during testing, Tables L & M summarize these tests.

At the inlet site between 50% and 80% of the particulate collected was at or below the 1 micron range. With the geometric mean diameter of the bulk of these particules approaching 0.5 microns.

At the outlet, the test indicates that the bulk of the particulate is in the 15 micron range. There was very little particulate evident in the submicron range.

These results indicate two possibilities. First, that there was a small rip or tear in one or more of the filter mesh allowing the particulate to slip through. Or secondly, that one of the filters types either the 150 x 150 plain weave or the 50 x 250 dutch weave, since the 325 x 325 twill was taken off line is prone to a "blowthrough" in the 15 micron range. Blowthroughs occur when a partial blinding of a filter forces a higher pressure to work on the still permeable section of the filter. Small pore-like holes open in the filter cake and allow the dust laden gas to rush through. A cake cannot re-form over these pores because of the high localized velocity of the gas. Combined, in this program, with the small size particulate which were unable to bridge the pore.

The first supposition that a rip was present, was checked when the MTU was disassembled for cleaning after the test program was completed. A small rip was found in filters element III B. Unfortunately this does not rule out the blowthrough theory. More testing would have to be performed to adequately address the problem.

F. Cleaning and Pressure Drop

Cleaning of the filters and the pressure drop across the MTU are two important factors in this test program. The fine nature of the particulate combined with the sticky properties it exhibited made the material easy to collect but difficult to clean.

At first glance the ΔP across the MTU seems high (25"-36" W.G.). Those figures are misleading. Any structure built to move air, or gas, has an inherent ΔP in the system. This inherent ΔP is present because gas is being forced through chambers or ductwork which may change direction or shape. In desiging a commercial installation, care is taken to arrange the gas carrying structures so that this inherent ΔP is kept low (on a range of 1"-2" W.G.).

But the MTU has more constraints placed upon it than a commercial installation. The Mobile Test Unit is designed to travel across country under standard tractors-trailer and road restrictions
This limits the size of the unit to the area of a conventional trailer. Roughly 8 ft. wide and no higher than 12.5 ft. More importantly the ductwork on the MTU had to be limited in diameter and restricted to sharp bends. In addition, the MTU is designed to serve not only as a demonstration device, but as a research tool.

The MTU is designed to be completely dismantled and reassembled by two men in under two days. This meant choosing a head system (to handle the clean gas as it moves towards the fan), which offered more in the area of easy maintainance than low ΔP.

As a result of this high inherent ΔP in the MTU, volumetric testing was performed (August 25-26, 1982) to determine the inherent ΔP. The results of these previous tests indicate the following:

	Fan Speed Setting	Inherent ΔP
Three Module Operations	8.5	23.0
Four Module Operations	8.5	17.0

F. Cleaning and Pressure Drop (Continued)

Therefore the ΔP due to the filter cakes, minus the approx. 1"W.G. of negative pressure in the duct, are as follows:

Test	Date	No. of Modules in use	Initial ΔP (WG)	Final ΔP (WG)
1	5/16/84	4	13.0	16.5
2	5/17/84	4	6.5	7.5
3	5/17/84	4	10.5	12.0
4	5/17/84	4	15.8	16.5
5	5/18/84	3	6.0	7.0
6	5/18/84	3	9.5	10.5
7	5/18/84	3	11.3	12.0
8	5/21/84	3	11.0	12.5
9	5/21/84	3	12.3	15.0
10	5/21/84	3	7.0	8.5

Cleaning the filter cake is the only method to control the ΔP. Ideally, after a filter had been cleaned the ΔP which has accumulated will drop back to the initial level. In practice finding the correct cleaning method for a given particulate, under a given set of conditions is a demanding task.

Because of the low particulate loading of the test gas stream (0.215-1.00 Gr/SDCF at the inlet) Vulcan Engineering decided to try to clean as seldom as possible. This was to avoid the problem of over cleaning and the resultant particulate passage.

After each test the filters were cleaned. At first the knives were allowed to complete a single revolution within the filters element while blowing compressed air at 40 PSI. This was later increased to 80 PSI and finally 100 PSI, when the cleaning had little effect upon the ΔP. Particulate was being removed from the filters (as evidenced by the collected particulate expelled from the hoppers of modules I and II), but at a rate slower than it was accumulating. The air knives were used while on line.

F. Cleaning and Pressure Drop (Continued)

The vibrators and rappers proved ineffective in cleaning. The mechanical energy produced by these devices was dissipated through the bulk of the MTU before it could reach the filter element.

Again at first, the pulsers sent three blasts of 40 PSI compressed air into the filters elements per cycle. This was later increased to 80 PSI and then 100 PSI. While the pulsers were more effecient than the air knives, there is still room for improvement.

The cleaning cycles were initated by hand, and fell into four statagies: cleaning every 5 minutes; cleaning every 15 minutes; cleaning every 1/2 hour, and cleaning only after the fan in the MTU was shut down and the system essentially was isolated.

Only the last stratagy proved to be really effective in controlling the ΔP. This shut down and cleaning was done at the end of each day. And on an intensive basis between tests 9 and 10.

The relatively small number of tests completed is due in part to the difficulty in cleaning the filters. May 22nd, was scheduled as a test day but the Vulcan Engineer had to cancel the day's test because of the severe cake build-up on the filters. The entire day was spent on cleaning the filters.

Additional studies and tests are required to assure repeatability of the cleaning process.

G. Grain Loading

Table J is a summary of the results of the grain loading aspects of this test program.

The inleakage had to be accounted for when considering the outlet grain loadings. The inlet of course not being affected. Table K is used in correcting for the leakage.

It is of interest to note that the inlet oxygen data is consistant for the first 8 tests, but increases dramatically for test 9 and 10. This would suggest either a change in the incinerator operation, or a sampling error.

On the subject of sampling errors. All stack testing is allowed to fall within a 90-110% isokinetic range. But out of twenty test runs (10 inlet and 10 outlet) there are seven runs that fall outside of the 90-110% limits. The most significant of these being test 8 at the outlet. The isokinetic rate in this case being only 69%. The six other runs were not as bad, but do throw some doubt on the results. Test 8 should not be considered a valid test.

Test 1 shows a very high outlet particulate loading in relation to the rest of the tests. It would appear that the pre-coat cake of lime was not properly built upon the filters. So that when the test began the particulate passed through open areas of the filter, until a cake did form.

More care was taken in the later tests to insure a proper cake build-up before beginning the particulate gas flow. Test 1 should not be considered a valid test.

The grain loading results have been reported in a pounds/ hour basis; a grains/SDCF basis corrected to inlet conditions; and a grains/SDCF basis is included to provide easy comparison to the incinerator standards which require results on a 50% excess basis.

H. HCL Removal

To be provided by Engineering Science Company

I. Particulate Sizing

A particulate sizing test was performed at the inlet and outlet sites once a day during testing. Tables L and M summarize these results.

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J - Tables
Results of Test #1
ENSCO/RTI
EL Dorado, AR.
May 16, 1984

Parameters	Inlet	Outlet
Time Start	15:50	15:52
Time Stop	16:32	16:53
$\%H_2O$	4.50	3.90
$\%CO_2$ (Vol.)	6.80	2.50
$\% O_2$ (Vol.)	12.10	19.90
Temp. (^0F)	740	360
ACFM	1900	2800
SDCFM (68^0F 29.92" Hg)	800	1700
Isokinetic Rate	99.50	96.40

Mobile Test Unit Conditions

Filter Area:	216 ft^2
ACR:	8.80
Filter Type:	25% 150 x 150, 25% 325 twill, 50% 50 x 250 D.W.
Lime Injection:	500 grams/15 min
Cleaning Device:	None During Testing
Pressure:	
Duration:	
Frequency:	
Pressure Drop:	31.0"----34.5"

J - Tables
Results of Test #2
ENSCO/RTI
EL Dorado, AR.
May 16, 1984

Parameters	Inlet	Outlet
Time Start	11:47	11:47
Time Stop	12:50	12:46
$\%H_2O$	16.80	9.20
$\%CO_2$ (Vol.)	7.00	3.20
$\% \ O_2$ (Vol.)	12.00	16.60
Temp. (^0F)	840	360
ACFM	1800	2500
SDCFM (68^{0}F 29.92" Hg)	600	1500
Isokinetic Rate	116.0	105.0

Mobile Test Unit Conditions

Filter Area: 216.0 Acr 8.33

Filter Type: 25% 150 x 150, 25% 325 Twill, 50% D.W.

ACR: 8.30

Lime Injection: Pre-Coat Only

Cleaning Device: I & II K, III & IV P

Pressure: 100 PSI

Duration: 1 Rev of K, 3 Pulses of 1 Second

Frequency: 15 Minutes

Pressure Drop: 24.5"----25.5"

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J - Tables
Results of Test #3
ENSCO/RTI
EL Dorado, AR.
May 16, 1984

Parameters	Inlet	Outlet
Time Start	14:09	15:52
Time Stop	16:32	16:53
%H_2O	4.50	3.90
%CO_2 (Vol.)	6.80	2.50
% O_2 (Vol.)	12.10	19.90
Temp. (^0F)	740	360
ACFM	1900	2800
SDCFM (68^{0}F 29.92" Hg)	800	1700
Isokinetic Rate	99.50	96.40

Mobile Test Unit Conditions

Filter Area:	216 ft^2
Filter Type:	25% 150 x 150, 25% 325 twill, 50% 50 x 250 D.W.
ACR:	8.80
Lime Injection:	500 grams/15 min
Cleaning Device:	None During Testing
Pressure:	
Duration:	
Frequency:	
Pressure Drop:	31.0"----34.5"

J - Tables
Results of Test #4
ENSCO/RTI
EL Dorado, AR.
May 16, 1984

Parameters	Inlet	Outlet
Time Start	16:00	15:59
Time Stop	17:05	16:59
%H_2O	20.90	8.60
%CO_2 (Vol.)	6.70	2.70
% O_2 (Vol.)	12.10	17.20
Temp. (^{0}F)	850	320
ACFM	1500	2300
SDCFM (68^{0}F 29.92" Hg)	500	1500
Isokinetic Rate	115.0	94.0

Mobile Test Unit Conditions

Filter Area:	216 ft^2
ACR:	6.94
Filter Type:	25% 150 x 150, 25% 325 Twill, 50% D.W.
Lime Injection:	Pre-Coat Only
Cleaning Device:	None During Testing
Pressure:	
Duration:	
Frequency:	
Pressure Drop:	33.80"----34.5"

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J - Tables
Results of Test #5

ENSCO/RTI
EL Dorado, AR.
May 16, 1984

Parameters	Inlet	Outlet
Time Start	08:31	08:32
Time Stop	09:33	09:31
%H_2O	23.90	10.00
%CO_2 (Vol.)	6.50	2.90
% O_2 (Vol.)	11.80	15.90
Temp. (^0F)	760	290
ACFM	1300	1600
SDCFM (68^{0}F 29.92" Hg)	400	1000
Isokinetic Rate	106.0	100.0

Mobile Test Unit Conditions

Filter Area:	162 ft^2
ACR:	8.02
Filter Type:	33% 150 x 150, 66% 50 X 250 D.W.
Lime Injection:	Pre-Coat Only
Cleaning Device:	Yes
Pressure:	100 PSI
Duration:	1 Rev K, 3 Pulses of 1 Second
Frequency:	1/2 Hour Time
Pressure Drop:	3.0"----31.0"

J - Tables
Results of Test #6
ENSCO/RTI
EL Dorado, AR.
May 16, 1984

Parameters	Inlet	Outlet
Time Start	10:05	10:10
Time Stop	11:08	11:22
%H_2O	19.50	8.60
%CO_2 (Vol.)	6.90	3.0
% O_2 (Vol.)	13.10	17.00
Temp. (^0F)	690	300
ACFM	984	2000
SDCFM (68^0F 29.92" Hg)	400	1300
Isokinetic Rate	95.0	87.0

Mobile Test Unit Conditions

Filter Area:	162 ft^2
ACR:	6.07
Filter Type:	33% 150 x 150, 67% 50 x 250 D.W.
Lime Injection:	Pre-Coat Only
Cleaning Device:	None During Testing
Pressure:	
Duration:	
Frequency:	
Pressure Drop:	33.5"----34.5"

J - Tables
Results of Test #7
ENSCO/RTI
EL Dorado, AR.
May 16, 1984

Parameters	Inlet	Outlet
Time Start	12:55	12:55
Time Stop	13:57	13:57
$\%H_2O$	20.20	8.60
$\%CO_2$ (Vol.)	7.50	3.00
$\%\ O_2$ (Vol.)	12.40	17.00
Temp. (^0F)	700	300
ACFM	1100	1800
SDCFM (68^0F 29.92" Hg)	400	1200
Isokinetic Rate	95.0	89.0

Mobile Test Unit Conditions

Filter Area:	162 ft^2
ACR:	6.79
Filter Type:	33% 150 x 150, 67% 50 x 250
Lime Injection:	Pre-Coat Only
Cleaning Device:	None During Testing
Pressure:	
Duration:	
Frequency:	
Pressure Drop:	35.25"----36.0"

J - Tables
Results of Test #8
ENSCO/RTI
EL Dorado, AR.
May 16, 1984

Parameters	Inlet	Outlet
Time Start	09:40	09:42
Time Stop	10:42	10:41
%H_2O	24.60	10.70
%CO_2 (Vol.)	6.00	3.00
% O_2 (Vol.)	12.50	15.90
Temp. (^{0}F)	650	290
ACFM	1200	1900
SDCFM (68^{0}F 29.92" Hg)	400	1200
Isokinetic Rate	100.0	69.0

Mobile Test Unit Conditions

Filter Area:	162 ft^2
ACR:	7.41
Filter Type:	33% 150 x 150, 67% 50 x 250
Lime Injection:	900 Grams/10 Minutes
Cleaning Device:	K & P
Pressure:	100 PSI
Duration:	1 Rev, 3 Pulses of 1 second
Frequency:	5 Minutes
Pressure Drop:	35.0"----36.5"

J - Tables
Results of Test #9
ENSCO/RTI
EL Dorado, AR.
May 16, 1984

Parameters	Inlet	Outlet
Time Start	09:00	09:01
Time Stop	10:01	13:57
%H_2O	13.40	5.60
%CO_2 (Vol.)	4.00	2.20
% O_2 (Vol.)	15.50	17.80
Temp. (^{0}F)	720	340
ACFM	1500	2000
SDCFM (68^{0}F 29.92" Hg)	580	1300
Isokinetic Rate	93.0	104.0

Mobile Test Unit Conditions

Filter Area:	162 ft^2
ACR:	9.26
Filter Type:	33% 67%
Lime Injection:	Pre-Coat Only
Cleaning Device:	None During Testing
Pressure:	
Duration:	
Frequency:	
Pressure Drop:	36.3"----39.0"

J - Tables
Results of Test #10
ENSCO/RTI
EL Dorado, AR.
May 16, 1984

Parameters	Inlet	Outlet
Time Start	12:15	12:13
Time Stop	13:34	13:30
%H_2O	14.0	7.70
%CO_2 (Vol.)	3.90	2.00
% O_2 (Vol.)	15.30	17.00
Temp. (^{0}F)	690	310
ACFM	1700	1900
SDCFM (68^{0}F 29.92" Hg)	670	1200
Isokinetic Rate	89.0	97.0

Mobile Test Unit Conditions

Filter Area:	162 ft^2
ACR:	10.50
Filter Type:	33% 150 x 150, 67% 50 x 250
Lime Injection:	Pre-Coat Only
Cleaning Device:	None During Testing
Pressure:	
Duration:	
Frequency:	1/2 Hour
Pressure Drop:	31.0"----32.5"

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COMPANY

TABLE K

Inleakage Calculations Oxygen Basis

ENSCO/RTI

MAY 14-25, 1984

TEST NUMBER	1	2	3	4	5	6	7	8	9	10
INLET O_2	12.1	12.0	11.7	12.1	11.8	13.1	12.4	12.5	5.5	15.3
OUT-LET	19.9	16.6	16.9	17.2	15.9	17.0	17.0	15.9	17.8	17.0
% OF INLEAKAGE	64.0	38.0	44.0	42.0	35.0	30.0	37.0	27.0	13.0	11.0

TABLE L
INLET PARTICLE SIZING
ENSCO/RTI
MAY 14-25, 1984

5/16/84 Stage	1	2	3	4	5	6	7
D50 (Microns)	17.05	10.61	4.85	3.08	1.50	0.64	---
Cumulative Percentage Smaller than D50	100.0	69.55	67.78	65.85	62.57	51.92	---
GEO Mean Diameter (Microns)	41.3	13.5	7.18	3.87.	2.15	0.98	0.45

5/18/84 Stage	1	2	3	4	5	6	7
D50 (Microns)	19.60	12.21	5.60	3.57	1.75	0.77	---
Cumulative Percentage Smaller than D50	100.0	92.55	92.42	92.33	92.33	82.65	---
GEO Mean Diameter (Microns)	44.30	15.50	8.27	4.47.	2.50	1.169	0.54

5/23/84 Stage	1	2	3	4	5	6	7
D50 (Microns)	19.15	11.92	5.46	3.48	1.70	0.74	---
Cumulative Percentage Smaller than D50	100.0	87.51	87.51	87.51	87.51	59.51	---
GEO Mean Diameter (Microns)	43.80	15.10	8.00	4.36.	2.43	1.12	0.52

*Aerodynamic Diameters Calculated according to the task group on lung dynamics.

TABLE M
OUTLET PARTICLE SIZING
ENSCO/RTI
MAY 14-25, 1984

5/17/84 Stage	1	2	3	4	5	6	7
D50 (Microns)	19.59	12.23	5.65	3.62	1.81	0.83	---
Cumulative Percentage Smaller than D50	100.0	67.38	53.21	40.91	25.40	14.97	---
GEO Mean Diameter (Microns)	44.30	15.50	8.31	4.52.	2.56	1.23	0.59

5/18/84 Stage	1	2	3	4	5	6	7
D50 (Microns)	19.64	12.26	5.67	3.64	1.82	0.84	---
Cumulative Percentage Smaller than D50	100.0	0.53	0.52	0.41	0.30	0.18	---
GEO Mean Diameter (Microns)	44.30	15.50	8.33	4.54.	2.57	1.23	0.59

5/23/84 Stage	1	2	3	4	5	6	7
D50 (Microns)	19.29	12.04	5.56	3.56	1.78	0.81	---
Cumulative Percentage Smaller than D50	100.0	34.03	22.25	19.36	14.88	9.47	---
GEO Mean Diameter (Microns)	43.%	15.20	8.18	4.45	2.52	1.20	0.57

*Aerodynamic Diameters Calculated according to the task group on lung dynamics.

Table N
Particulate Removal Efficiency
ENSCO/RTI
El Dorado, AR

Test Number	Inlet Loading (lb/M)	Outlet Loading (lb/Hr)	Outlet * Loading (Grains/ SDCF)	System Efficiency	Outlet ** Loading (Grains/ SDCF)
1	1.4112	0.9281	0.1744	34.20	0.2803
2	3.6657+	0.2526	0.0205	93.10	0.0322
3	3.8481+	0.3678	0.0516	90.40	0.0755
4	4.1481+	0.0426	0.0426	92.50	0.0685
5	2.5368	0.1477	0.0257	94.20	0.0378
6	1.5571	0.2440+	0.0317+	84.30	0.0566
7	2.5112	0.2680+	0.0405+	89.30	0.0660
8	3.7319	0.9402+	0.1234+	74.80	0.2027
9	2.3026	0.2300	0.0242	90.00	0.0605
10	5.1093+	0.0840	0.0091	98.40	0.0234
Average++	3.2099	0.2380	0.0307	91.50	0.0526

* Corrected to Inlet Conditions.

** Corrected to 7% Oxygen, 50%. Excess Air (Using P54-55 North American Combustion Handbook)

+ Unsatisfactory Isokinetic Sampling Rate

++ Excluding Tests 1 and 8

VULCAN
ENGINEERING
COMPANY
DIVISION OF UMEC CORPORATION

V A. PRELIMINARY TEST PROGRAM
ENSCO INCINERATOR
EL DORADO, ARKANSAS

This program is subject to change at the discretion of Vulcan Engineering Company. This is to insure the safety of the Hi-TAC Test Unit under the acidic conditions of the gas stream being tested. Also, the test program may be changed if results indicat more promising data in a particular instance.

May 9, 1984

Arrive before 3:30 p.m.
Position trailer,
Contact Don Johnson about utilities and duct connections;
Complete what is possible that day.
Unload heater.

May 10, 1984

Position heater; hook up transition piece.
Connect utilities.
Connect duct.
Check slide gate on duct.
Check out heater for travel damage.
Test heater.
Check out Mobile Unit for travel damage.
Install insulation blankets.

May 11, 1984

Perform actual start-up to include:

1) Use of heater to bring unit to 300-400 degrees F.
2) Feed pre-coat.
3) Draw stack gas.

   a) Check temperature with 4/2 modules.
   b) Check P at 3200 and 1600 ACFM.

Perform complete shut down.

V A. Preliminary Test Program (Continued)

May 14 & 15, 1984

3240 ACFM

216 Ft^2

LiO pre-coat

May 16 & 17, 1984

1620 ACFM

108 Ft^2

LiO pre-coat

May 18, 1984

LiO pre-coat

Voulmetric flow rate to be determined on site

May 21 & 22, 1984

3240 ACFM

216 Ft^2 filter media

Soda ash pre-coat

May 23 & 24, 1984

1620 ACFM

108 Ft^2 filter media

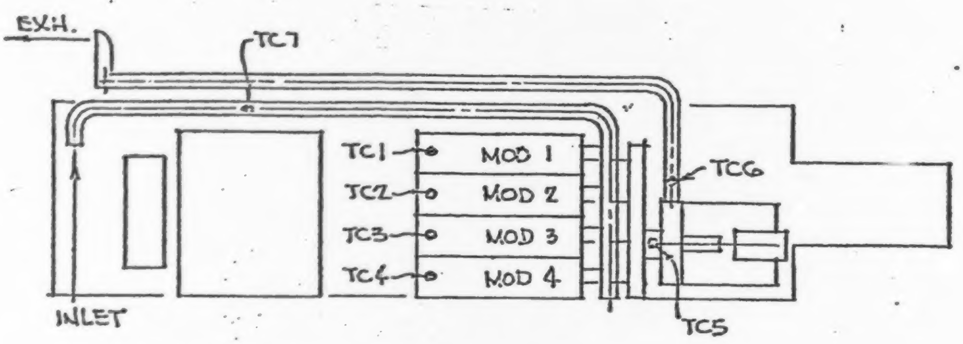
Soda ash pre-coat

May 25, 1984

Soda ash pre-coat

Volumetric flow rate to be determined on site

V B. Diagram of Hi-TAC Temperature & Pressure Sensors

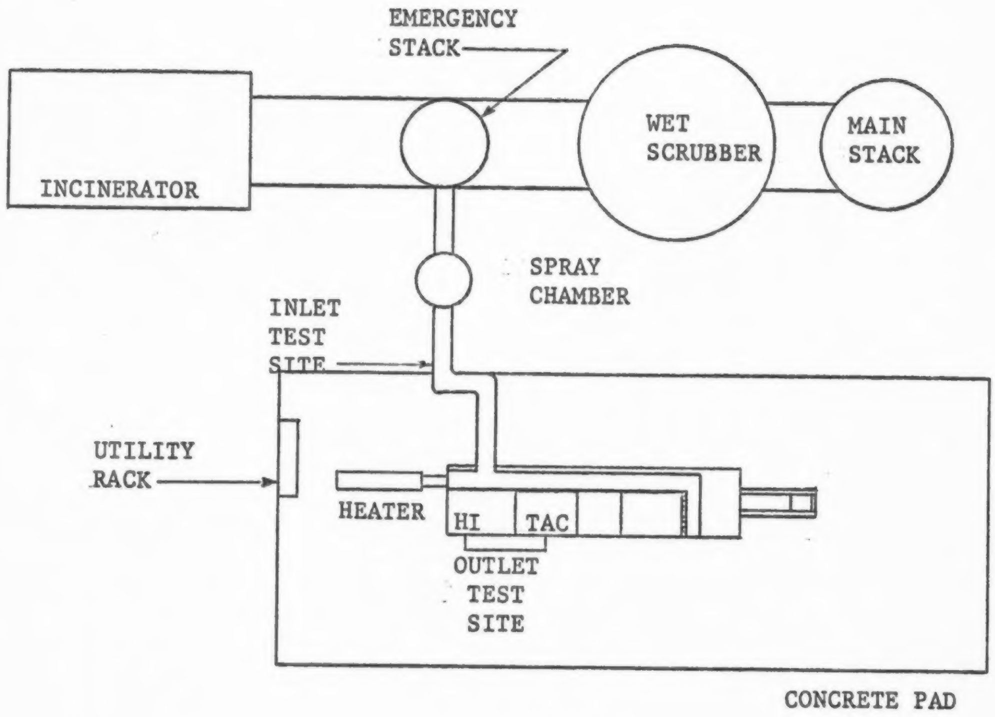

EXH.
TC7
TC1
TC2
TC3
TC4
MOD 1
MOD 2
MOD 3
MOD 4
TC6
TC5
INLET

LOCATION OF THERMOCOUPLES

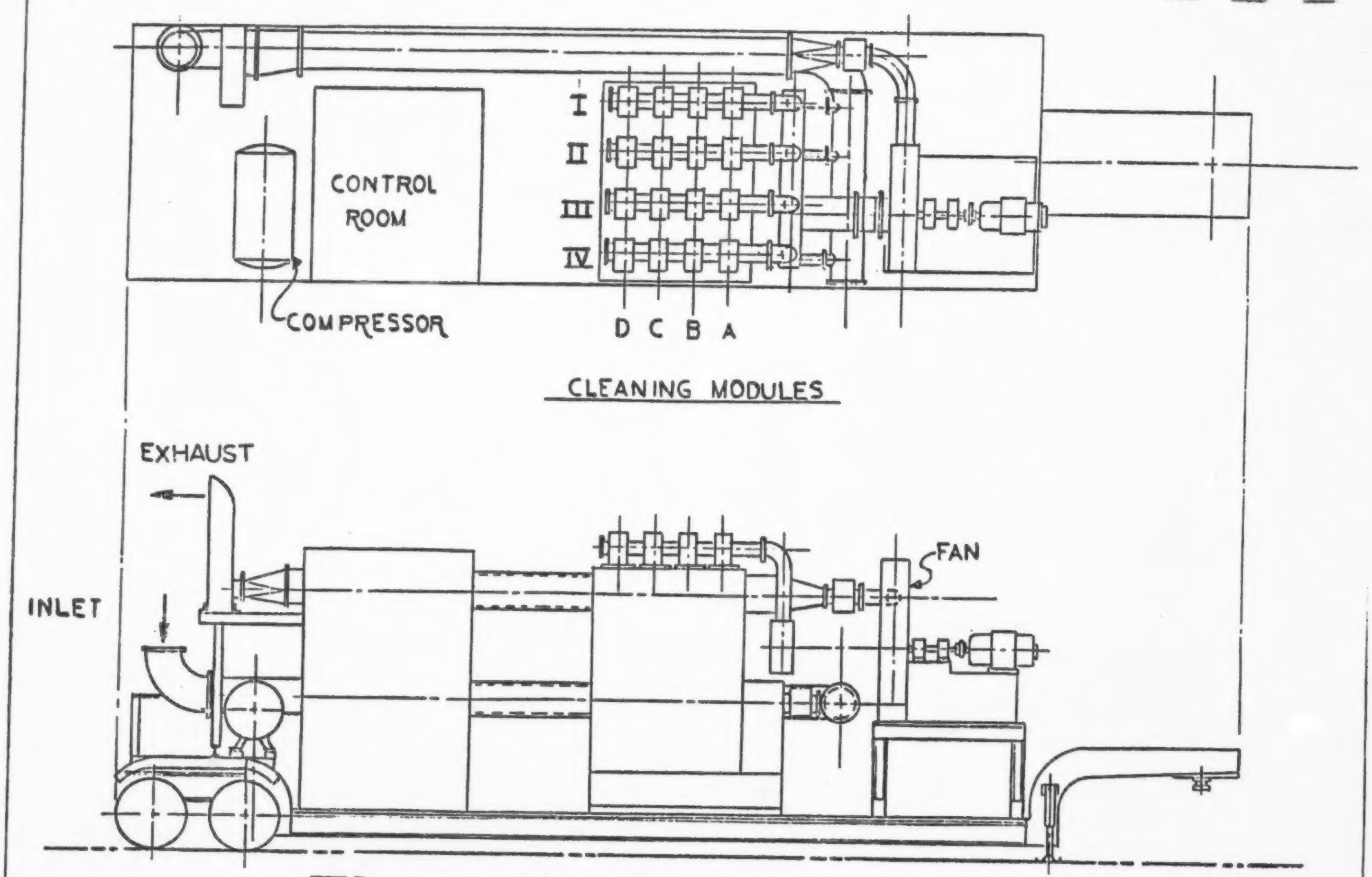
The temperature recorder is a 12 pt. Honeywell Model.
The temperature range is 0-1200 degrees fahrenheit.
The chart should be read as a percentage of the range.

Example: Number 7 thermocouple records at 15 on the chart temperature = (0.15 x 2000) = 300 degrees fahrenheit.

Point: Number 8 is not a temperature monitor. It is the output from the _P (pressure drop) transmitter. The range of the range of the transmitter is 0-50" W.G.


EMERGENCY
STACK
INCINERATOR
WET
SCRUBBER
MAIN
STACK
SPRAY
CHAMBER
INLET
TEST
SITE
UTILITY
RACK
HEATER
HI
TAC
OUTLET
TEST
SITE
CONCRETE PAD

V C. PLOT PLAN
ENSCO INCINERATOR
TEST SET UP


CONTROL ROOM
COMPRESSOR
I
II
III
IV
D C B A
CLEANING MODULES
EXHAUST
INLET
FAN

V.D HI-TAC MOBILE UNIT

FIGURE II